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Southwest Research Inst, San Antonio, Tex

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ASSESSMENT OF CONTROL TECHNIQUES FOR REDUCING EMISSIONS FROM LOCOMOTIVE ENGINES

by

John O. Storment

Karl J. Springer

FINAL REPORT

Contract EHS 70-108

Task VI

Prepared for

Transportation Systems Center

U. S. Department of Transportation

and

Characterization and Control Development Branch

Mobile Source Pollution Control Program

Office of Air and Water Programs

Environmental Protection Agency

April 1973

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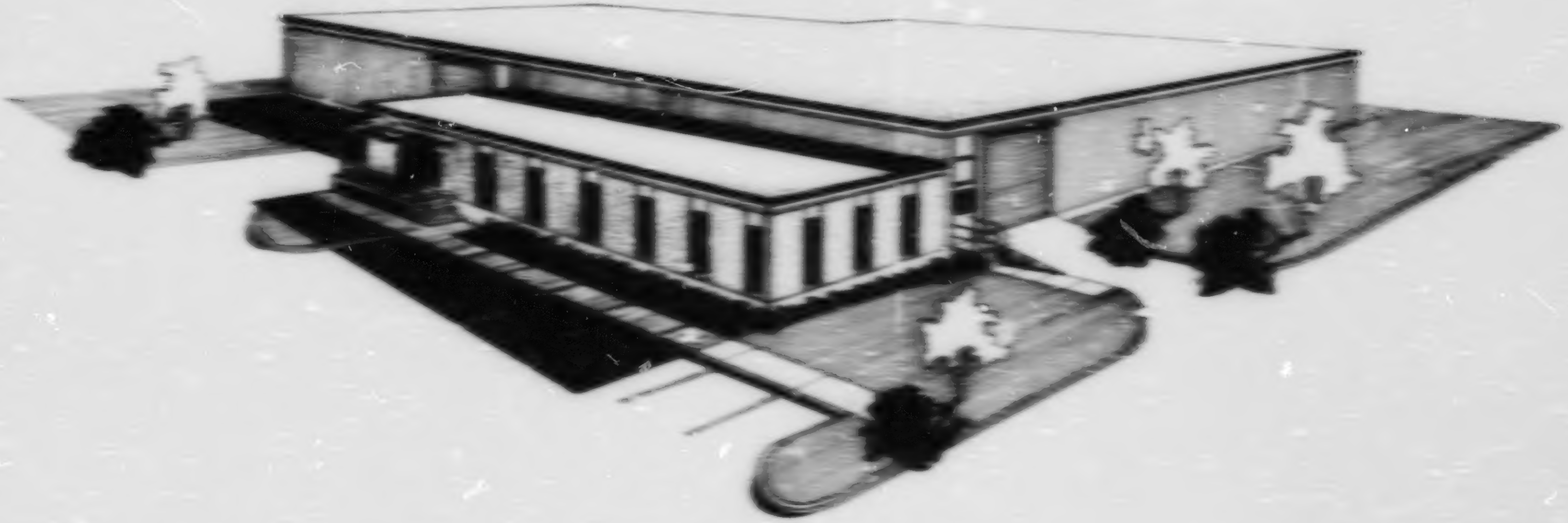

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FOREWORD

This project was performed for the U.S. Department of Transportation's Transportation Systems Center by the Emissions Research Laboratory of Southwest Research Institute. The project was an outgrowth of SwRI Proposal No. 11-8750, dated May 16, 1972, entitled "Assessment of Control Techniques for Reducing Emissions from Locomotive Engines". Test work began in November, 1972, and was completed in March, 1973.

The project contract was administered by Mr. William Rogers Oliver of EPA. Project funding was by DOT, with funds transferred to EPA for management purposes. The Project Officer responsible for technical direction of the project was Dr. Karl M. Hergenrother of the Transportation Systems Center.

Project Manager for SwRI was Karl J. Springer, Manager of the Emissions Research Laboratory. Supervision of test work, data reduction, and report preparation was by John O. Storment. The lead technician on the project was Raul Martinez, and he was ably assisted by Gene Hoyt and Rodney Bauer. Alan Rittiman, Shop Foreman, furnished valuable assistance in setting up the test engine. Execution of the project was aided by the valuable advice of Mr. Hugh Williams, Jr., of EMD Engineering.

ABSTRACT

The primary objective of this study was to determine the most effective method of reducing emissions of oxides of nitrogen from a two-cylinder version of an EMD series 567C locomotive engine. The control method judged most effective was that which resulted in the greatest reduction in NO_x, had the least adverse effects on other emissions constituents and engine operation, yet was simple to install and maintain.

The NO_x control techniques selected for use in this study included (1) change in fuel injector design, (2) variation in injection timing from the standard setting, (3) inlet air humidification (water induction), (4) reduction of scavenging air volume (air box bleed), and (5) exhaust gas recirculation (EGR). In addition, methods (2) and (3) were used in combination. Continuous measurements of unburned hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NO_x), and smoke opacity were made as the test engine was operated through a test cycle based on speed and load points characteristic of actual locomotive operation.

Results of these tests indicated that the most effective control method was retarded injection timing (4° from standard). The next most effective method was EGR, with the recirculated exhaust cooled to 125-150° F. It was necessary to derate (or reduce) engine power at certain points in order to maintain smoke opacity at acceptable levels with both of these control techniques. Water induction, whether used with standard or retarded timing, was moderately effective in reducing NO_x, but not as effective as retarded timing alone. Air box bleed was not as effective as cooled EGR, and had the serious drawback of producing excessive smoke and CO. Hot (or uncooled) EGR resulted in substantial reductions in NO_x, but also produced extremely high levels of smoke and CO. It was necessary to drastically derate engine power to reduce smoke to acceptable levels. Finally, it was found that the new low-sac injectors were superior to the older needle-valve in the areas of HC and smoke control, but were inferior in the amount of NO_x produced. These relative differences in the two types of injectors were maintained when the various control methods were used.

I. INTRODUCTION

A. Background

The Emissions Research Laboratory of Southwest Research Institute has been engaged for several years in a series of programs to furnish information to various government agencies on emissions from a variety of sources. One such program, performed under Contract No. EHS 70-108 ("Exhaust Emissions From Vehicles and Related Equipment Using Internal Combustion Engines"), is concerned with a study of emissions from power sources such as used in lawnmowers, motorcycles, outboard motors, farm and construction equipment, and railroad locomotives.

The item of work in EHS 70-108 involving locomotive engines has been completed, and a report issued in October, 1972(1). Three locomotives were tested; one powered by a four-stroke cycle G. E. engine and two units powered by two-stroke cycle EMD engines, one turbocharged and one naturally aspirated. This study was concerned only with characterization of the emissions from these three locomotives, with no effort expended in the area of control technology. And although EMD and, possibly, G. E. have programs underway to reduce emissions such as smoke and oxides of nitrogen, the two principal emissions of current interest and importance, no work in this area was being conducted by the Federal Government.

The work that is the subject of this report was performed as a sub-phase of Contract EHS 70-108. This arrangement was justified by the fact that the Emissions Research Laboratory had gained valuable experience and information concerning EMD engines in the course of the previous locomotive work. Also, the Department of Automotive Research at SwRI was in possession of a suitable test engine with which to evaluate the various exhaust emission control methods. This test engine was of the same general type as the engine in one of the locomotives (Unit No. 1311) tested previously. There thus existed a data base which could be used as reference for the data from the initial tests of the basic (unmodified) test engine.

B. Objectives

The principal objective of this project was to provide an assessment of various techniques for controlling oxides of nitrogen from a locomotive-type diesel engine operating over typical switch and line-haul duty cycles. The effectiveness of these techniques was to be evaluated and their influence on hydrocarbons, carbon monoxide and, especially, smoke opacity determined. The overall effectiveness of the various control methods could then be established. Attempts were to be made to alleviate, or at least enumerate, any adverse effects of the control techniques on other emissions or engine operation.

C. Approach

Several control techniques which were known to influence NO_x emission from smaller, automotive-type diesel engines were selected for use in the project. These techniques were evaluated using a two-cylinder version of an Electro-Motive Division (EMD) series 567 locomotive engine. This engine was operated over a test cycle made up of speed and load points typical of a full-size 567 engine. Continuous measurements were made of unburned hydrocarbons, carbon monoxide, oxides of nitrogen, and smoke opacity. A computer program was developed which calculated cycle composite brake specific emissions, as well as brake specific and fuel specific emissions on a modal basis. Two weight factor schedules--one designed around switch or rail yard service and the other around line haul service--were used in performing these calculations. Use of these two sets of time-based weighting factors permitted the effectiveness of a given control technique to be determined for both types of duty cycles.

D. Progress Reports and Project Review

Monthly progress reports were furnished to the Project Officer at DOT and the Contract Administrator at EPA. These reports summarized the items of work accomplished during the reporting period, results of the test work, and brief statements on future project plans and the status of project funds. Many telephone conversations were held with the Project Officer in order to keep him abreast of project status and to solicit technical advice. The Project Officer visited SwRI on December 14, 1972, for an extensive project review. In addition, Mr. Louis Roberts, Director of Technology for DOT's Transportation Research Center, visited the Emissions Research Laboratory on March 14, 1973, and was given a briefing on the project.

II. TEST ENGINE, FUEL, AND INSTRUMENTATION

This section of the report offers a description of the engine used in this study, an analysis of the test fuel, and a description of the instrumentation used to obtain gaseous emissions data.

A. Description of Test Engine

The engine used in this study (Figure 1) was a two-cylinder version of the Electro-Motive Division (EMD) model 567, a blower scavenged, two-stroke cycle engine which, in 8, 12, and 16 cylinder form, is a principal power source for diesel locomotives. The engine has a displacement of 567 cu. in. per cylinder and a maximum governed speed of 835 rpm. The engine is connected to a 1000-hp capacity EMD generator, which is in turn connected to a load bank capable of absorbing 400 hp.

The full-size 567 engine is presently in use in a variety of configurations. Hence, it was necessary to decide which configuration would be representative of most in-service 567 engines. The aid of EMD was formally requested in a letter, dated July 24, 1972, to Mr. Hugh A. Williams, Jr., of EMD Engineering. Mr. Williams responded with a letter which contained information concerning such engine variables as compression ratio, type of cylinder liners and injectors, and injection timing. This letter also contained information and advice about possible engine test cycles. The letter appears as Appendix A of this report.

Based on the information thus obtained, it was decided to equip the test engine with 20-port cylinder liners, 16:1 compression ratio pistons, and fuel injectors calibrated for the medium air flow range of this engine. These components are basic to the 567C model engine, many of which are in use in 8, 12, and 16 cylinder versions.

B. Test Fuel Analysis

The fuel used throughout the project was the No. 2 emissions test fuel specified for use in Federal smoke and emissions certification tests of heavy-duty, automotive-type diesel engines. However, this fuel was used in the project because analysis revealed it to be very much like three typical diesel fuels used by Southern Pacific. An analysis of these three fuels was done in the course of on-site emissions tests performed by Southwest Research on three locomotives at the SP yard(1).

The analysis of the test fuel used in the current project is given in Table 1.

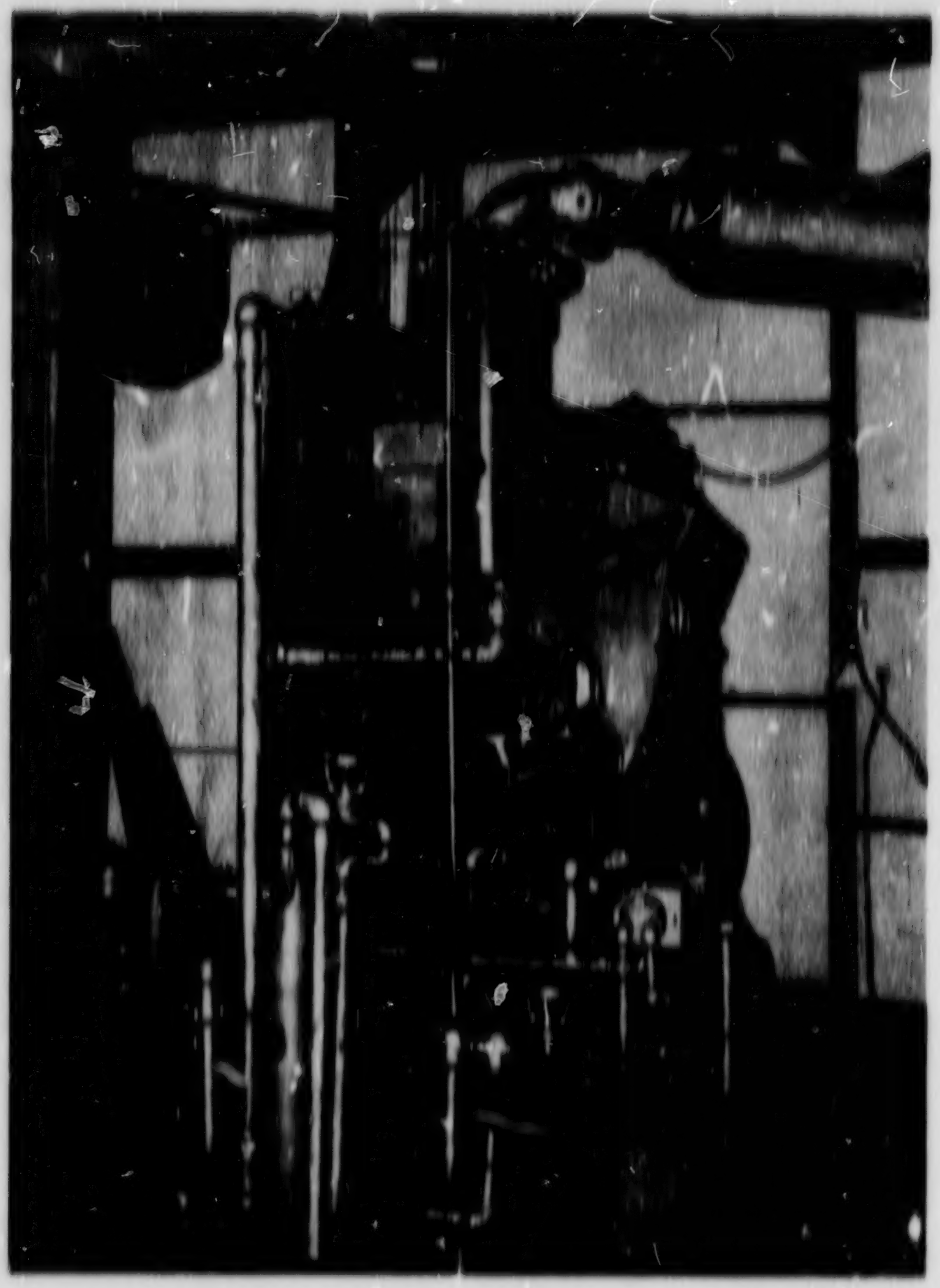


FIGURE 1. EMD 2-567 TEST ENGINE AND INSTALLATION

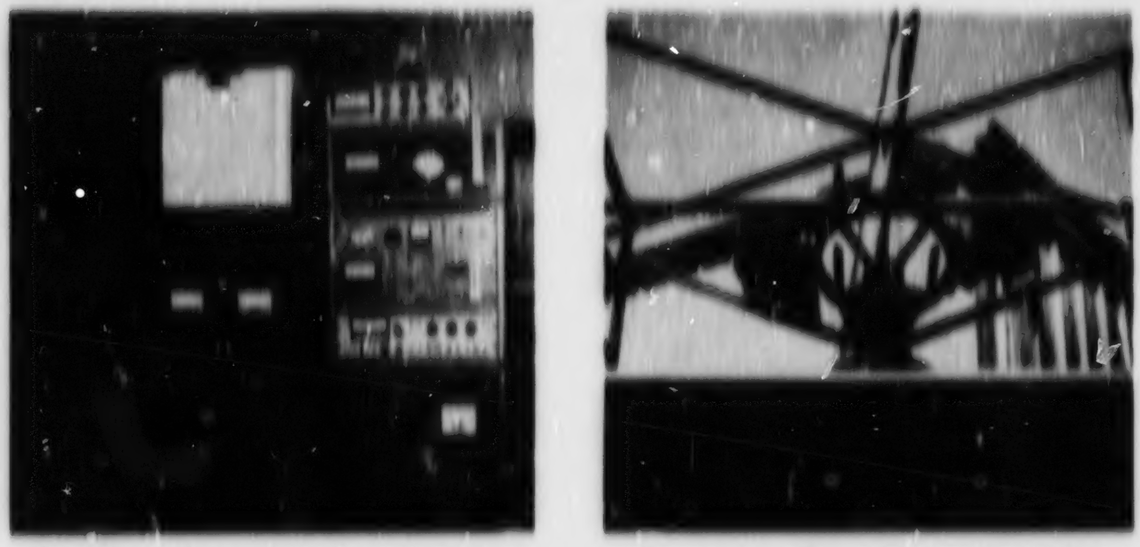
TABLE I. LABORATORY ANALYSIS OF TEST FUEL

Fuel Type	DF-2
Property	
Gravity, °API	34.5
Sulfur, % by wt.	0.3
Aromatics, %	37.6
Distillation, °F	
Initial Boiling Point	386
End Point	658
10%	436
20%	461
30%	481
40%	498
50%	514
60%	530
70%	546
80%	564
90%	605
95%	648
Recovery, %	99.0
Residue, %	1.0
Calculated Cetane No.	46.7

C. Emission Instrumentation and Measurement Devices

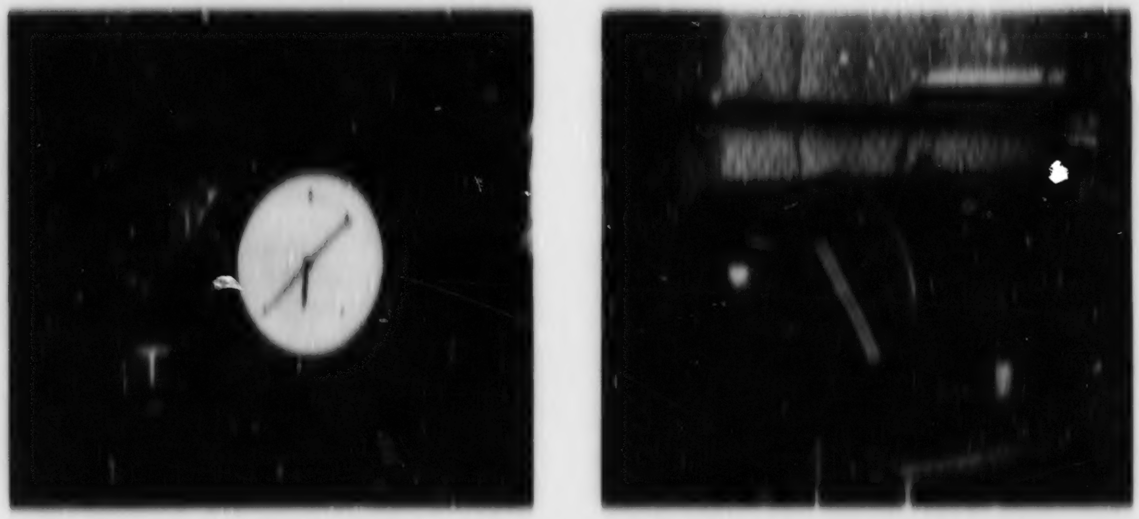
Measurements of unburned hydrocarbons, carbon monoxide, carbon dioxide, oxides of nitrogen (NO_x), and smoke opacity were taken during all tests. Excess oxygen in the exhaust was measured during tests conducted in the later stages of the project. Hydrocarbons (HC) were measured by a heated FID unit built to specifications given in SAE Recommended Practice J215. Carbon monoxide and carbon dioxide were measured by non-dispersive infrared analyzers in a system that conforms to SAE Recommended Practice J177, while oxides of nitrogen were measured by a chemiluminescent analyzer. Oxygen measurements were obtained by a polarographic analyzer. Exhaust smoke opacity was measured by means of an enlarged version of the PHS smokemeter. This enlarged model, built on a 20-in diameter ring instead of the 10-in diameter ring of the normal unit, proved to be a reliable and accurate instrument. The optical head was mounted on a six-in diameter exhaust pipe with the centerline of the light beam four in. from the end of the pipe.

Engine fuel consumption was measured by a Flo-Tron linear mass flowmeter with direct readout in pounds per hour. A heat exchanger was used to keep fuel temperature in the range of 90-100°F. Engine air consumption was measured by means of long-radius nozzles that conform to SAE Recommended Practice J244. Several views of the instrument cart, smokemeter, and fuel and air measurement devices are shown in Figure 2.



A. Emissions Sampling Cart for Diesel HC, CO, CO$_2$, and NO$_x$

B. Large Size (20-in dia.) PHS Smokemeter



C. Linear Mass Flowmeter and Indicator for Fuel Measurement

D. Long Radius Nozzles for Measurement of Engine Air Flow

FIGURE 2. TEST INSTRUMENTATION FOR MEASUREMENT OF EMISSIONS CONCENTRATIONS, SMOKE, AND FUEL AND AIR FLOW

III. NO_x CONTROL METHODS AND PROJECT TEST PLAN

The objective of this project was to determine the effectiveness of several possible methods for control of locomotive exhaust emissions, particularly emissions of oxides of nitrogen. Several methods which were known to influence NO_x emissions in smaller, automotive-type diesel engines were selected for this study. These methods, and the engine modifications necessary to implement them, are outlined in this section. The test plan which was developed around these control methods is also presented here.

A. NO_x Control Methods

The control methods selected for use with the test engine included (1) fuel injectors of different designs, (2) variation of injection timing, (3) inlet air humidification (water induction), (4) reduction of scavenging air volume (air box bleed), and (5) exhaust gas recirculation (EGR).

Three types of injectors are currently in use in EMD locomotive engines: an older style, known as the spherical-valve injector, which is used in many older engines, but is no longer manufactured; a newer style, called the needle-valve injector, which is used in most later model engines; and the newest type of injector, known as the low-sac, which was introduced by EMD in mid-1972(2). The principal design difference in these three types of injectors is in the sac volume below the spherical or needle valve that controls fuel flow through the injector. The sac volume has been steadily reduced by these design changes, principally to reduce exhaust smoke opacity and hydrocarbons. It was decided that all three types of injectors should be tested in the project in order to determine their effect on gaseous emissions.

The effect of injection timing on smoke opacity and NO_x from diesel engines is well known (i.e., later injection causes higher smoke but less NO_x), so it was decided that tests should be performed with non-standard timing. The standard timing setting for all EMD engines is 4° BTC. It was recommended by EMD that timing be varied ±4° of the standard setting (letter from Hugh Williams, contained in Appendix A). Injection timing is easily changed on the test engine.

Inlet air humidification (or water induction) was accomplished by mounting two atomization nozzles directly above the blower inlet. Water flow rate (in pounds per hour) was determined for various flowmeter settings. Air was supplied to the atomization nozzles at a constant pressure. Water was inducted at a mass flow rate equal to 25, 50, 75, or 100 percent of the fuel flow mass per mode. The same water rate (as a percent of fuel rate) was used in all modes of a given test.

Reduction of scavenging air (air box bleed) results in incomplete scavenging of exhaust gases from the cylinders and, consequently, a dilution of the incoming air charge. Hence, a kind of internal exhaust gas recirculation is obtained. This method works, of course, only with two-stroke cycle engines. Air box bleed of the test engine was accomplished by means of a three-in diameter gate valve installed in the air box (Figure 3A). A three-in OD pipe containing a plate orifice and a thermocouple was attached to this valve. The pressure drop across the orifice, the static pressure differential, and the temperature of air at the orifice were monitored in order to calculate the mass of the by-pass air (in pounds per minute). Air bleed rates were equal to 10, 20, 35, and 50 percent of the total air flow mass requirement of the engine per mode. The air bleed rate (as a percentage figure) was held constant throughout a given test.

Tests involving exhaust gas recirculation were done using "cooled" and "hot" exhaust gases. In both cases the exhaust gases were taken from a plenum chamber at the top of the engine. A three-in diameter gate valve was installed in this plenum chamber to regulate the flow of exhaust gases (Figure 3B). To obtain cooled EGR the exhaust gases were passed through a large water-cooled heat exchanger before entering the engine air intake system (Figure 3C). The heat exchanger was cooled by water from an external source rather than from the engine cooling system. This allowed the recirculated exhaust gas to be cooled to 125-150°F, a temperature range that might be difficult to obtain in actual locomotive operation unless an efficient air-cooled heat exchanger were used. The EGR flow rates chosen were 10, 20, and 30 percent of intake air mass requirement per mode. However, in the actual test work the rates were approximately 7, 16, and 25 percent of air flow mass. These reduced rates nevertheless indicate the correlation between EGR and engine smoke and gaseous emissions. The EGR rates will be referred to as "nominal" 10, 20, and 30 percent rates.

To obtain hot EGR the recirculated exhaust was routed around the heat exchanger. Exhaust temperatures in the EGR line were approximately 200-800°F, depending on engine speed and load. The hot recirculated exhaust was, of course, mixed with cool air in the inlet system before entering the engine. The EGR rates were again somewhat below the nominal 10, 20, and 30 percent rates chosen for this series of tests.

The recirculated exhaust, whether cooled or hot, passed through a straight section of three-in OD pipe containing a plate orifice and thermocouple. The orifice pressure drop, static pressure differential, and temperature of the gas at the orifice were used to compute the mass of the recirculated exhaust. The exhaust then entered the engine air intake system at a point between the air cleaner and the blower.

B. Test Plan

The tests performed in the course of the project are outlined by the

A. Air Box Bleed Valve and Line at Rear of Engine

B. External EGR Line and Vertically-Mounted Heat Exchanger

C. External EGR Line Entering Engine Air Inlet System

FIGURE 3. EXTERNAL ENGINE MODIFICATIONS FOR AIR BOX BLEED AND EXHAUST GAS RECIRCULATION

following matrix.

		Nonstd. Timing		Water Induction			Exh. Gas Recir.	
Injectors	Standard Timing	Adv.	Retd.	Std. Timing	Retd. Timing	Air Box Bleed	Cooled	Hot
Spherical	X							
Needle	X	X	X	X	X	X	X	X
Low-Sac	X		X	X	X	X	X	X

The tests at standard timing were used to determine the improvement in emission characteristics that could result from merely changing to a newer-style injector, and also to provide the reference (for needle and low-sac injectors) needed to evaluate the effectiveness of the various control methods. Since all spherical-valve injectors now in use will eventually be replaced by newer types, they were not used in the tests involving the control techniques. On the other hand, the majority of in-service EMD engines are equipped with either needle-valve or low-sac injectors; hence, these injectors were used for the full range of tests. However, some tests with the low-sac models were omitted in order to derive maximum benefit from the time and funds available. In particular, the low-sac injectors were used with only one water rate and retarded timing, rather than with all four water rates, and two of the four air box bleed rates and one of the three EGR rates were not done.

The actual test sequence involved (1) tests with spherical-valve injectors at standard timing, (2) all tests with needle-valve injectors, and (3) all tests involving low-sac injectors. Hence, injectors were not removed until the completion of all tests with a given type.

IV. TEST CYCLE AND DATA REDUCTION

This section describes the test cycle used throughout the project, the rationale behind development of the cycle, and the steps performed to reduce raw data to its final form.

A. Engine Test Cycle

It was deemed desirable to formulate a test cycle which would be representative of locomotive engine operation for this model engine, could be used for all tests regardless of changes in engine configuration from one test series to another, and would be as short as possible and still allow emission levels to stabilize.

Locomotive engines typically operate at certain engine speeds that are obtained by placing the throttle in predetermined positions or "notches". Fuel rate in each throttle position is also predetermined, so that engine power is constant for a given engine speed. Electro-Motive Division engines in line-haul (non-switch) service have eight throttle positions, plus low idle, while engines in switch service are equipped with a continuous-position throttle. The 2-567 test engine was equipped with a continuous-position throttle, but it was decided to operate the engine at speeds which corresponded to the eight throttle positions of a model 16-567C engine with 16:1 compression ratio pistons and medium air flow range injector tips.

The test plan called for several series of tests with different engine configurations produced by changing from one NO_x control method to another. Some, if not all, of these different engine configurations would undoubtedly result in changes in engine power output. It was therefore decided that the test cycle should not involve engine power as a parameter. Thus, engine fuel consumption rate and speed were the quantities which were used to define the test points (modes) of the cycle. A schedule of fuel rates for various EMD engines was obtained from the manufacturer. Fuel rates for the test cycle were obtained by dividing the typical 16-567C fuel rates by a factor of eight.

The test cycle was completed by adding three modes at low idle speed to the eight test points already selected, thus making an 11-mode schedule. The final form of the cycle is given in Table 2.

Initial emission tests with this cycle indicated that four-minute modes were sufficiently long to allow engine speed and load changes and stabilization of emission levels. This 44-minute long cycle formed the basis for all test work in the project. Repeatability of test results was generally good, though not exceptional. Particular problems that occurred during the tests will be mentioned in the section dealing with test results.

TABLE 2. TEST CYCLE FOR EMISSION TESTS OF EMD 2-567C ENGINE

Mode	Notch Position	Engine Speed, rpm	Fuel Rate, lbs/hr
1	Low Idle	285	-
2	1	285	4.0
3	2	344	11.8
4	3	424	21.2
5	4	515	32.5
6	Low Idle	285	-
7	5	584	45.6
8	6	675	60.0
9	7	755	75.6
10	8	835	93.8
11	Low Idle	285	-

B. Recording and Reduction of Data

All data were recorded during the last minute of each mode of the test cycle. Hydrocarbon emissions were measured "wet", that is, without allowing water vapor in the sample to condense. Emissions of CO, CO_2, and NO_x were measured "dry", after water vapor was removed from the sample by means of ice baths and/or a drying agent. Other data recorded at this time included engine speed and load (in terms of generator output), fuel flow, pressure differential across the long-radius nozzles, smoke opacity, and various temperatures and pressures dealing with ambient conditions and engine operation. Ambient wet/dry air temperatures and observed barometric pressure were recorded two or three times during the 44-minute test.

Most of this raw data was entered into a computer program developed for this project. The computer printouts, which appear in Appendix B, provide a detailed summary and analysis of the test data and results. The top half of the printout is concerned with engine performance data and parameters, such as engine speed and power output, mass flow rates for fuel, air and exhaust, fuel-air ratio (later changed to excess oxygen-fuel ratio) and brake specific fuel consumption, and various engine operating temperatures and pressures. The lower half of the printout contains exhaust smoke opacity, emission concentrations, weighting factors (later changed to excess oxygen), and brake specific and fuel specific values for hydrocarbons, carbon monoxide and oxides of nitrogen (as NO_2). All of these data are given on a modal basis. Cycle composite brake specific values of HC, CO, NO_x (as NO_2) and brake specific fuel consumption are also given. Emission concentrations that are measured "dry" appear on the printout as "wet" values after conversion by one of the conversion factors in SAE Recommended Practice J177. Concentration values of NO and NO_x

are further corrected to a standard atmospheric moisture content of 75 grains of water per pound of dry air by the conversion factor approved by the Environmental Protection Agency for diesel engine certification tests[3].

Two weight factor schedules are used in computing the cycle composite brake specific quantities. One schedule represents the duty cycle of a locomotive engaged in switch operation[4], while the other schedule represents the cycle of a line-haul locomotive[5]. The two weighting schedules are given in Table 3.

TABLE 3. LOCOMOTIVE WEIGHT FACTOR SCHEDULES

Mode	Notch Position	Engine Speed, rpm	Percent of Operating Time in Notch ATSF Switch	 G.E. Line Haul
1	Low Idle	255	25.7	14.3
2	1	285	10.0	3.0
3	2	344	5.0	3.0
4	3	424	4.0	3.0
5	4	515	2.0	3.0
6	Low Idle	255	25.7	14.3
7	5	584	1.0	3.0
8	6	675	1.0	3.0
9	7	755	0	3.0
10	8	835	0	28.0
11	Low Idle	255	25.7	14.3

The ATSF schedule assumes that a switch engine is at low idle some 77 percent of its operating time. Hence, each of the three idle modes in the test cycle have weight factors of approximately 25.7 percent. The weight factors become progressively smaller as the throttle notch position increases, thus reflecting the small amount of time such an engine spends in the higher horsepower ranges. Indeed, notches 7 and 8 (modes 9 and 10) have weight factors equal to zero.

The G. E. line-haul schedule gives low idle a weight factor of 43 percent, so that each idle mode is weighted by 14.3 percent. Each of the first seven notches consumes three percent of the operating time of the line-haul cycle, while notch 8 (mode 10), the point of maximum power output, is given 28 percent of the operating time. It should be noted that the sum of the weight factors given above is only 92 percent. This is because the G. E. schedule contains a mode for application of the dynamic brake. This condition, which has an eight percent weight factor attached to it, was deleted for purposes of this project. This deletion was necessary, since the test engine did not have the dynamic brake, and justified, since the weighting schedule remains the same for all cycle composite calculations and thus produces brake specific values that can be compared in a relative sense.

It is evident from this discussion that the cycle composite values are highly dependent on the particular set of weight factors used in the calculations, and this dependence should be kept in mind whenever cycle composite values are being discussed. It should also be noted that the weight factors do not have any effect on modal brake specific and fuel specific quantities. However, fuel specific emissions for idle modes are heavily influenced by the fuel rates, since only these fuel rates were uncontrolled. That is, idle fuel rates experienced normal fluctuations, while fuel rates in all other modes were held close to the predetermined values shown in Table 2. These fluctuations also produced relatively large differences in the cycle composite brake specific fuel consumption values, since these values are heavily weighted towards the low idle condition, regardless of the weight factor schedule used. In short, fuel specific emissions at idle (Modes 1, 6, and 11) and cycle composite BSFC values should be interpreted in light of the fact that normal fluctuations in idle fuel consumption play a large part in the differences in these values.

V. SUMMARY OF TEST RESULTS

This section summarizes the results of all tests performed in the project. Principal results presented here include the cycle composite brake specific HC, CO, and NO_x (as computed with both ATSF and G. E. weight factor schedules), the modal smoke opacity, and the (unweighted) modal brake specific and fuel specific emissions. Modal concentrations of HC, CO, and NO_x are summarized in the subsections concerned with air box bleed and cooled and hot EGR. The tables and figures for these modal quantities (except smoke opacity) are contained in Appendix C to avoid cluttering the text, and will be referred to as required. Computer printouts of the calculated test results are contained in Appendix B.

Because this study was a research effort into a relatively unknown area, it was a great advantage to consult with personnel at EMD Engineering about various problems and results encountered in the course of the project. Several telephone conversations were held between the staff of the Emissions Research Laboratory and EMD, and qualitative results of several phases of the test work were discussed. EMD confirmed the general trend of the SwRI results in several areas of testing, including tests with three types of fuel injectors, non-standard injection timing, and water induction. These confirmations served to build confidence in the results and hasten the test schedule along.

Before proceeding to the analysis of the test results, it is necessary to issue a word of caution on one point. The results of this study were obtained from a series of tests in a controlled laboratory environment, using a two-cylinder version of a full-size EMD series 567 locomotive engine. The relationship between this experimental situation and the situation which exists for a typical locomotive in switch or line haul service is not known. Therefore, extreme care should be used in projecting the results of these tests to the railroad industry as a whole, or even to all EMD model 567 in-service engines.

A. Emissions For Three Types of Injectors at Standard Timing

These results characterize the emission levels of the test engine when equipped with three types of injectors set to standard timing (4° BTC). The results also furnish a set of baseline values for needle and low-sac injectors that will be used to evaluate the effectiveness of the various control methods.

Table 4 summarizes the average cycle composite brake specific emissions from Tables B-1 to B-28 of Appendix B. These average values are illustrated in Figures 4 and 5. Comparing the composite values calculated with ATSF weight factors, it was found that brake specific hydrocarbons (BSHC) were reduced by about 49 percent by changing from

TABLE 4. CYCLE COMPOSITE BRAKE SPECIFIC EMISSIONS FOR EMD 2-567 ENGINE WITH SPHERICAL-VALVE, NEEDLE-VALVE, AND LOW-SAC INJECTORS AT STANDARD TIMING

Injectors	BSHC	BSCO	$BSNO_x$	$BSHC + BSNO_x$
		ATSF Weight Factor Schedule		
Spherical	8.842	4.081	19.823	28.665
Needle	4.553	4.139	19.562	24.115
Low-Sac	1.837	3.702	22.563	24.400
		G. E. Weight Factor Schedule		
Spherical	2.680	6.251	12.121	14.801
Needle	1.106	10.568	9.823	10.929
Low-Sac	0.655	7.281	13.045	13.700

spherical-valve to needle-valve injectors, while a 60 percent reduction resulted when changing from needle to low-sac injectors. A 79 percent reduction in BSHC was noted between the spherical and low-sac models. Cycle composite brake specific CO (BSCO) was almost the same for the spherical and needle injectors, while the low-sac injectors reduced this value by about 34 percent. Similarly, the brake specific NO_x ($BSNO_x$) was very nearly the same for the spherical and needle injectors, but the low-sac model raised this value approximately 13 percent.

It has been previously mentioned that an earlier phase of Contract EHS 70-109 involved testing of three locomotives, one (No. 1311) of which was powered by an EMD 12-567 engine. This engine was equipped with needle-valve injectors and 16:1 compression ratio pistons, but operated at slightly different speeds than the test engine in some notch positions. Fuel rates per cylinder were very close for the two engines. The cycle composite emissions for this locomotive were calculated with ATSF switch weight factors only. It is interesting to compare these values with those obtained from the 2-567 engine in the baseline tests. The respective BSHC, BSCO, and $BSNO_x$ for the two engines are given below.

Engine	BSHC	BSCO	$BSNO_x$
12-567	8.87	3.89	11.40
2-567	4.55	4.14	19.56

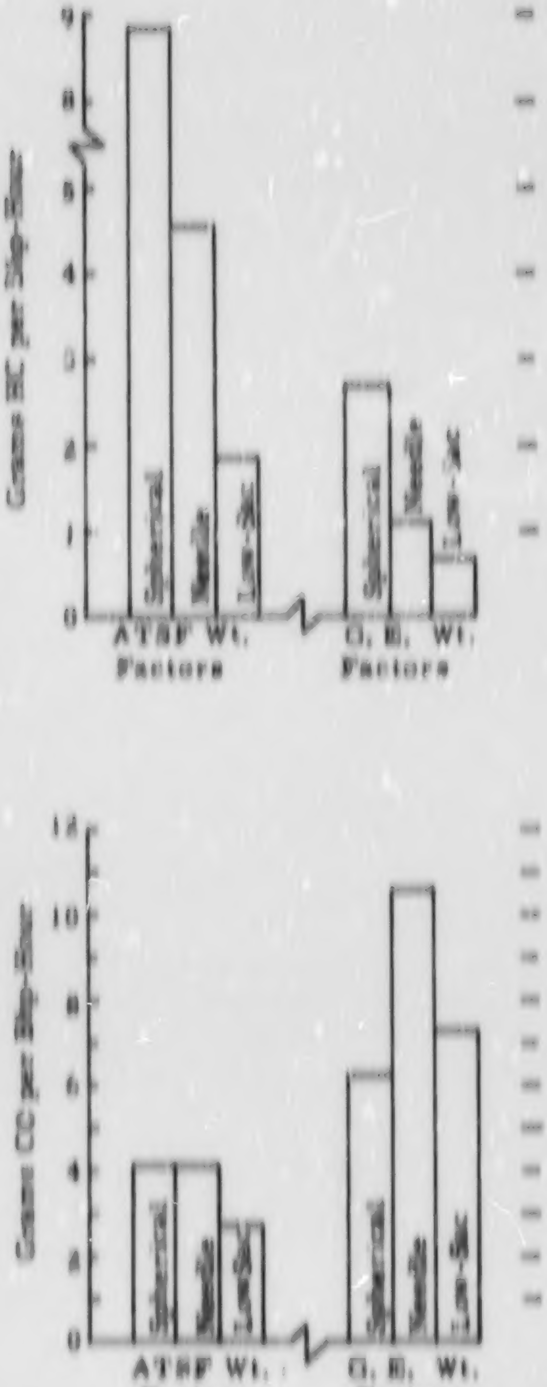


FIGURE 4. CYCLE COMPOSITE BRAKE SPECIFIC HC AND CO FOR EMD 2-567 ENGINE EQUIPPED WITH THREE TYPES OF FUEL INJECTORS AT STANDARD TIMING

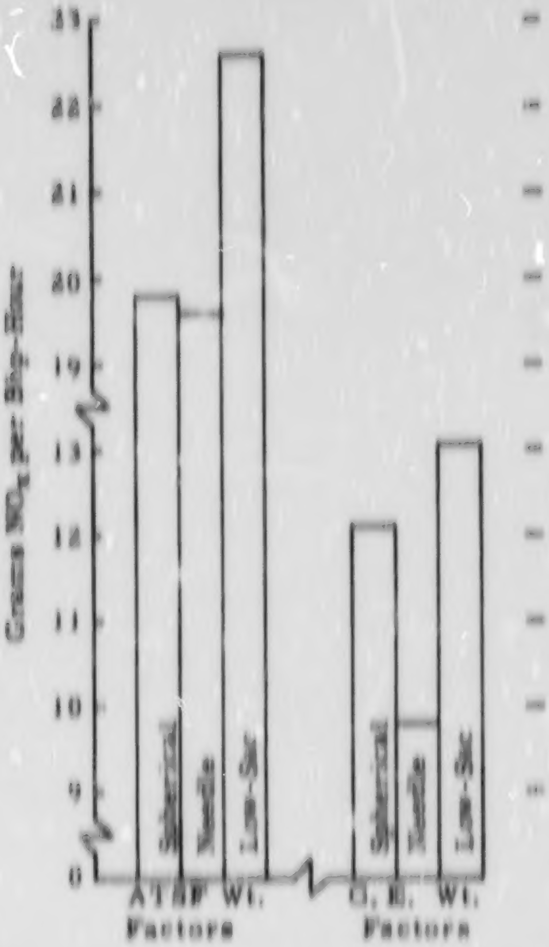


FIGURE 5. CYCLE COMPOSITE BRAKE SPECIFIC NO$_x$ FOR EMD 3-567 ENGINE EQUIPPED WITH THREE TYPES OF FUEL INJECTORS AT STANDARD TIMING

It is evident that only the BSCO values are approximately equal, while BSHC differs by a factor of nearly two, and BSNO$_x$ by slightly less. The cause of these rather large differences lies in the concentrations of HC and NO$_x$; the 12-cylinder engine simply produced higher concentrations of the former and lower concentrations of the latter than did the 3-567 test engine.

A comparison of the cycle composite brake specific values computed with G. E. weight factors reveals that the needle injectors produced almost 59 percent less BSHC than did the spherical injectors, while a 41 percent reduction occurred between the needle and low-sac models. These latter injectors produced some 75 percent less BSHC than the spherical injectors. The needle and low-sac injectors gave, respectively, 69 and 14 percent more BSCO than the spherical models. The needle injectors produced about 19 percent less BSNO$_x$ than the spherical units, while the low-sac injectors gave seven percent more than the spherical valves and 25 percent more than the needle-valves.

The average modal smoke opacity for the three types of injectors is given in Table 5 and shown in Figure 6. It is evident that smoke opacity was low in all cases. This is not surprising, since the engine was equipped with new pistons and cylinder liners, and the injectors were either new or recently rebuilt. It is interesting to note that the opacities measured during these tests are very similar to those measured during on-site tests of the 12-567 engine in Unit No. 1311[6].

TABLE 5. MODAL SMOKE OPACITY FOR SPHERICAL-VALVE, NEEDLE-VALVE, AND LOW-SAC INJECTORS AT STANDARD TIMING

Mode	Notch Position	Engine Speed, rpm	PHS Smoke Opacity, % Spherical Inj.	Needle Inj.	Low-Sac Inj.
1, 6, 11	Low Idle	285	1.4	0.8	1.0
2	1	285	1.5	1.4	1.2
3	2	344	2.0	1.5	1.2
4	3	424	2.0	1.9	1.3
5	4	515	2.0	1.7	2.3
7	5	584	2.0	1.4	1.8
8	6	675	2.0	1.8	2.3
9	7	755	3.0	2.6	2.5
10	8	835	3.9	4.6	3.8

Average modal brake specific and fuel specific emissions are presented in Table C-1 and Figures C-1 through C-6 in Appendix C. The spherical injectors gave the highest BSHC in every mode or notch position, and the low-sac injectors gave the lowest values (Figure C-1). The spherical and needle injectors produced much more BSHC in notch positions 1-3 (285-424 rpm) than in the remaining test modes. The low-sac models were characterized by fairly constant output of BSHC in all notch positions. The spherical injectors produced the highest BSCO in the lower notch positions, while the low-sac units gave the least (Figure C-2). However, in the upper notch positions the needle injectors produced the most BSCO, and the spherical units gave the lowest values. The behavior of these modal BSCO values, and a brief consideration of the two sets of weight factors involved, illustrate why the rank order of the cycle composite BSCO values discussed previously was changed by the use of the two weighting schedules. The spherical injectors produced the most $BSNO_x$ in the first two notch positions, but the low-sac models resulted in the highest values in all the other positions. The needle injectors gave the lowest values in all but the first notch. Again, the somewhat inconsistent trend of these modal values, when interpreted in light of the two weighting schedules, explains the behavior of the cycle composite values.

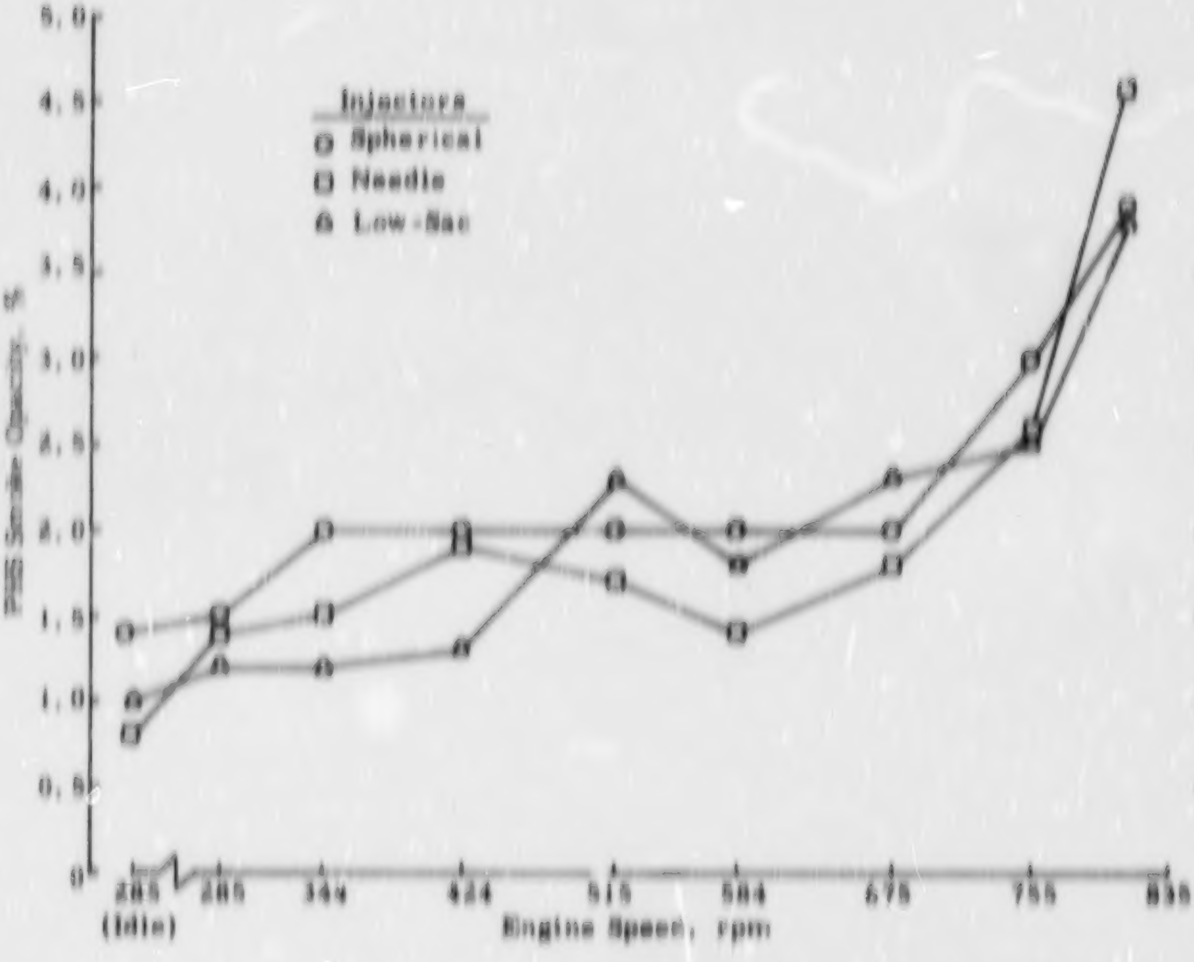


FIGURE 5. MODAL SMOKE OPACITY LEVELS FOR THREE TYPES OF FUEL INJECTORS AT STANDARD TIMING

Modal fuel specific data is derived from the mass flow (in grams per hour) of HC, CO, or NO_x, divided by the fuel flow (in pounds per hour). The emission mass flow is basically a function of intake air mass and the concentration of the particular contaminant. Since the mass of intake air and fuel per mode remained fairly constant from one test to another, a given fuel specific value is essentially a function of concentration. The only test points where this analysis is in doubt is at low idle (Modes 1, 6, and 11), where fluctuations in fuel flow produced differences in the associated fuel specific quantities that were not caused by differences in concentrations alone.

Fuel specific HC (Figure C-4) values for the three types of injectors show the same trends as the brake specific HC, with the spherical injectors yielding the highest values and low-sacs the lowest. The fuel specific CO (Figure C-5) values also follow the same trend as their brake specific counterparts, with spherical injectors producing the highest values in the lower notch positions and needle models giving the most FSCO in the higher notches. At low idle condition the low-sac units produced the most CO and the spherical models the least. The $FSNO_x$ of the spherical injectors differs from that of the other two types of injectors not only in magnitude but also in its behavior in the first condition (Figure C-6). This difference is apparently due to a change in the fuel rates at low idle. This change occurred a short time after the baseline tests of the spherical injectors. In any case, the low-sacs produced the most FSCO, and the needle valve units generally produced the least.

Engine power output was fairly constant, regardless of which type of injector was used. The power recorded was observed and not corrected for changes in ambient conditions. Hence, some variation was present, but it is not thought that these differences in power are related to injector design. Engine operation was also unaffected by the different injectors, i.e., there was no roughness or instability of operation present.

In summary, it can be said that the needle and low-sac injectors produced much lower brake specific HC than the spherical-valve models. Unfortunately, the low-sacs produced higher $BSNO_x$ than either of the other two types of injectors. Brake specific CO was not significant in any instance. It should be noted that the observed relative effects of injector type on emissions is very similar to those found in the case of an automotive two-stroke cycle diesel of the same general design as the 8-567 engine(7). The three types of injectors used in the study referenced are known as crown-valve, needle-valve, and LSN (Low Smoke Nozzle), and are very similar to the spherical-valve, needle-valve, and low-sac injectors of the present study.

B. Effect of Injection Timing On Emissions--Needle-Valve and Low-Sac Injectors

A series of tests was performed with the needle and low-sac injectors set to nonstandard timing. Needle injectors were tested at two such settings, 4° advanced and 4° retarded from the standard 4° BTC. The low-sac units were tested at the retarded setting only.

Table 6 and Figures 7 through 10 summarize the cycle composite brake specific emissions for these tests. The corresponding computer printouts are Tables B-29 through B-48 of Appendix B. As usual, computations were performed with both weight factor schedules.

With needle injectors, standard timing resulted in the highest BSHC (Figure 7) and advanced timing gave the lowest values. These results held true regardless of the weight factor schedule used in the calculations. Likewise, BSCO values computed with ATSF weight factors were highest for standard timing and lowest for the advanced setting (Figure 7). However, when computed with G. E. weight factors, the BSCO was highest with retarded timing and lowest with advanced timing. This difference is due to the fact that retarded timing produced much higher CO concentrations in notches 5 to 8 (584 to 835 rpm), which are weighted more in the G. E. line haul schedule than in the ATSF switch schedule.

The very important cycle composite values of $BSNO_x$ are shown in Figure 8. As expected, retarded timing produced the lowest values and advanced timing gave the highest. With ATFF weight factors, $BSNO_x$ values with retarded timing were approximately 32 percent lower than with standard timing and about 55 percent less than with advanced timing. Using G. E. weight factors, retarded timing gave about 25 percent less $BSNO_x$ than the standard timing and some 46 percent less than for advanced timing. In all cases, the improvement in the cycle composite $BSNO_x$ was significant and was accomplished with a simple engine modification. The only apparent drawback, in a gaseous emission sense, was the increased CO concentrations in the high-power notch positions.

Retarded timing of the low-sac injectors resulted in slightly lower BSHC and slightly higher BSCO (Figure 9) than was obtained with standard timing. Brake specific NO_x (Figure 10) was reduced by 26 percent for the ATSF cycle and by 28 percent for the G. E. cycle. These brake specific values therefore follow the same trend, relative to the values for the needle injectors, as in the baseline tests; i.e., at retarded timing the low-sac produced less BSHC and BSCO, and more $BSNO_x$ than the needle-valve units.

Table 7 contains the smoke opacity data for both types of injectors at the various timing settings, and Figure 11 illustrates these data. Looking first at the data for the needle injectors, it is evident that retarded timing led to a substantial opacity increase in notches 5 to 8 (584 to 835 rpm). However, the increased opacity was excessive only at the notch 8 position. Another series of tests was performed at retarded timing but with a slight power derating in notch 8. The amount of derating used was

TABLE 6. EFFECT OF INJECTOR TIMING ON CYCLE COMPOSITE BRAKE SPECIFIC EMISSIONS FOR NEEDLE-VALVE AND LOW-SAC INJECTORS

Injectors	Injector Timing	BSHC	BSCO	$BSNO_x$	$BSHC + BSNO_x$
		ATSF Weight Factor Schedule			
Needle	Std. (4° BTC)	4.553	4.139	19.562	24.115
	4° Retd.	3.562	3.988	13.226	16.788
	4° Adv.	2.685	1.946	29.586	32.271
Low-Sac	Std. (4° BTC)	1.837	2.702	22.563	24.400
	4° Retd.	1.715	3.194	16.572	18.287
	4° Adv.	*	*	*	*
		G.E. Weight Factor Schedule			
Needle	Std. (4° BTC)	1.106	10.568	9.823	10.929
	4° Retd.	1.041	12.500	7.326	8.366
	4° Adv.	0.839	10.051	14.060	14.899
Low-Sac	Std. (4° BTC)	0.655	7.281	13.045	13.700
	4° Retd.	0.605	9.783	9.378	9.791
	4° Adv.	*	*	*	*

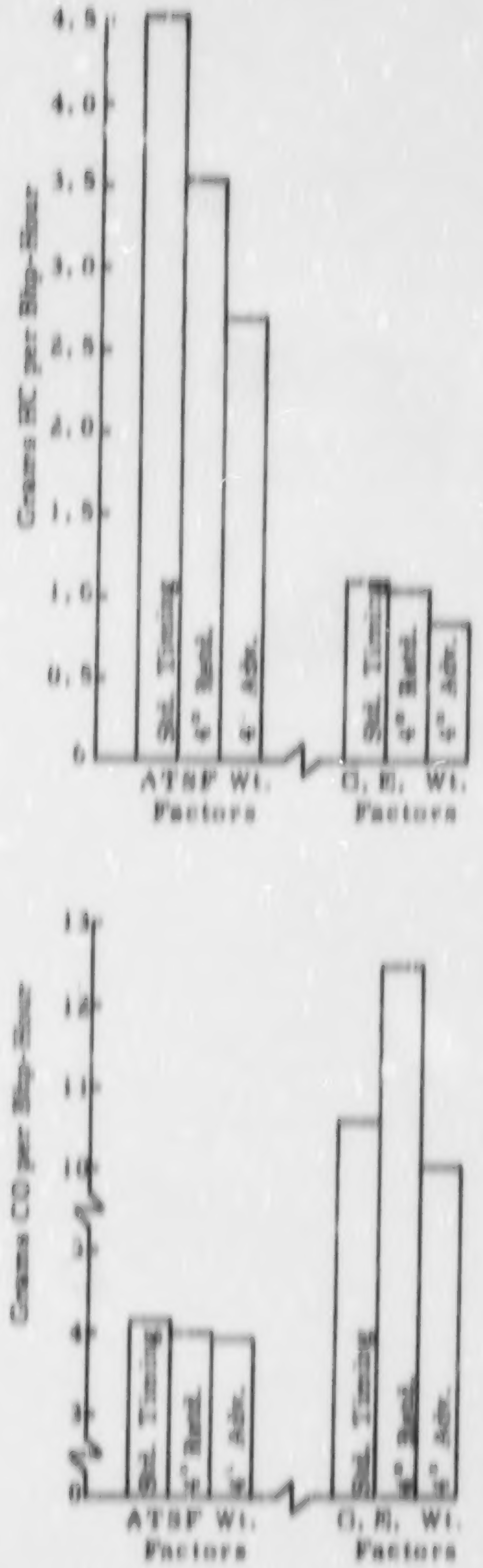


FIGURE 7. CYCLE COMPOSITE BRAKE SPECIFIC HC AND CO FOR NEEDLE-VALVE INJECTORS AT THREE TIMING SETTINGS

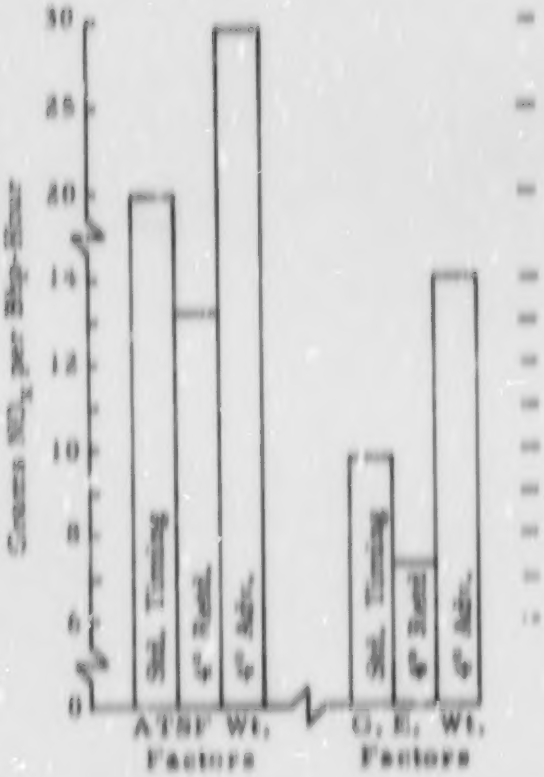


FIGURE 5. CYCLE COMPOSITE BRAKE SPECIFIC NO_x FOR NEEDLE-VALVE INJECTORS AT THREE TIMING SETTINGS

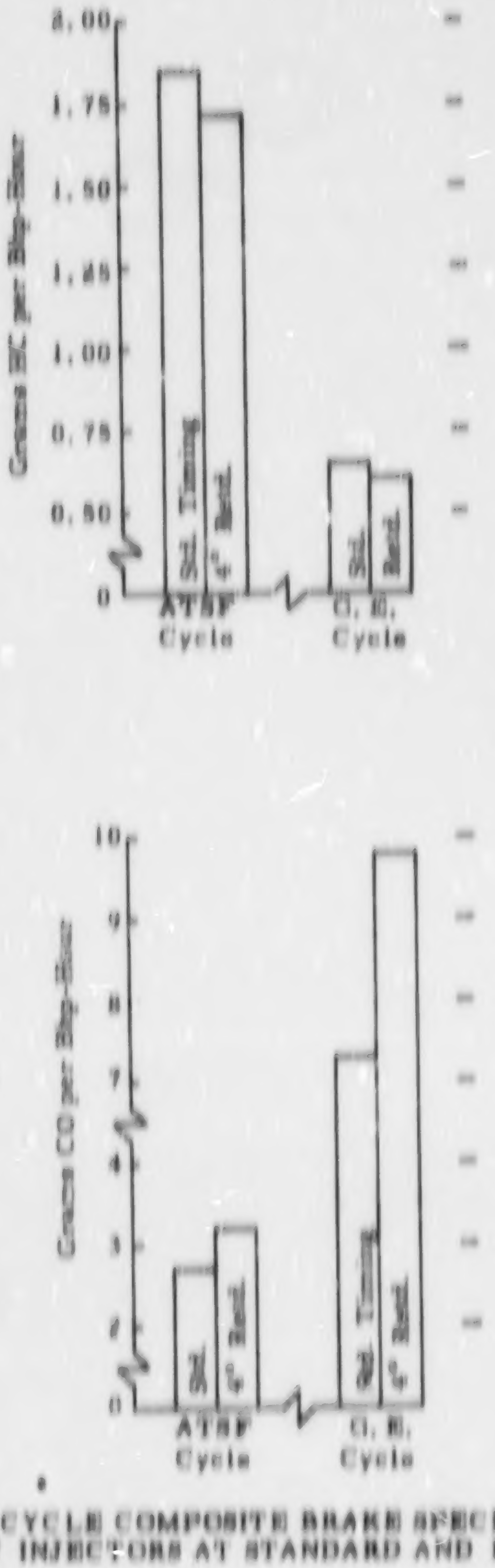


FIGURE 9. CYCLE COMPOSITE BRAKE SPECIFIC HC AND CO FOR LOW-SAC INJECTORS AT STANDARD AND RETARDED TIMING

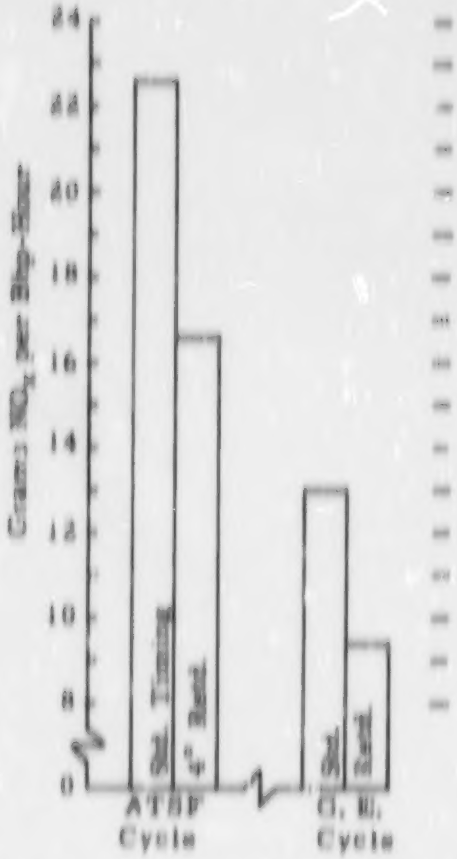


FIGURE 10. CYCLE COMPOSITE BRAKE SPECIFIC NO_x FOR LOW-SAC INJECTORS AT STANDARD AND RETARDED TIMING

TABLE 7. EFFECT OF INJECTION TIMING ON SMOKE OPACITY FOR NEEDLE-VALVE AND LOW-SAC INJECTORS

Mode	Notch Position	Engine Speed, rpm	PHS Smoke Opacity, %		
			Std. Timing	4° Adv.	4° Retd.
	Needle Injectors				
1, 6, 11	Low Idle	285	0.8	1.1	1.8
2	1	285	1.4	1.2	2.0
3	2	344	1.5	1.2	2.0
4	3	424	1.9	1.3	2.1
5	4	515	1.7	1.2	2.3
7	5	584	1.4	1.4	2.8
8	6	675	1.8	1.3	3.5
9	7	755	2.6	1.7	5.5
10	8	835	4.6	2.7	10.0
	Low-Sac Injectors				
1, 6, 11	Low Idle	285	1.0	-	1.0
2	1	285	1.2	-	1.5
3	2	344	1.2	-	1.8
4	3	424	1.3	-	1.8
5	4	515	2.3	-	2.0
7	5	584	1.8	-	1.8
8	6	675	2.3	-	2.2
9	7	755	2.5	-	3.0
10	8	835	3.8	-	5.7

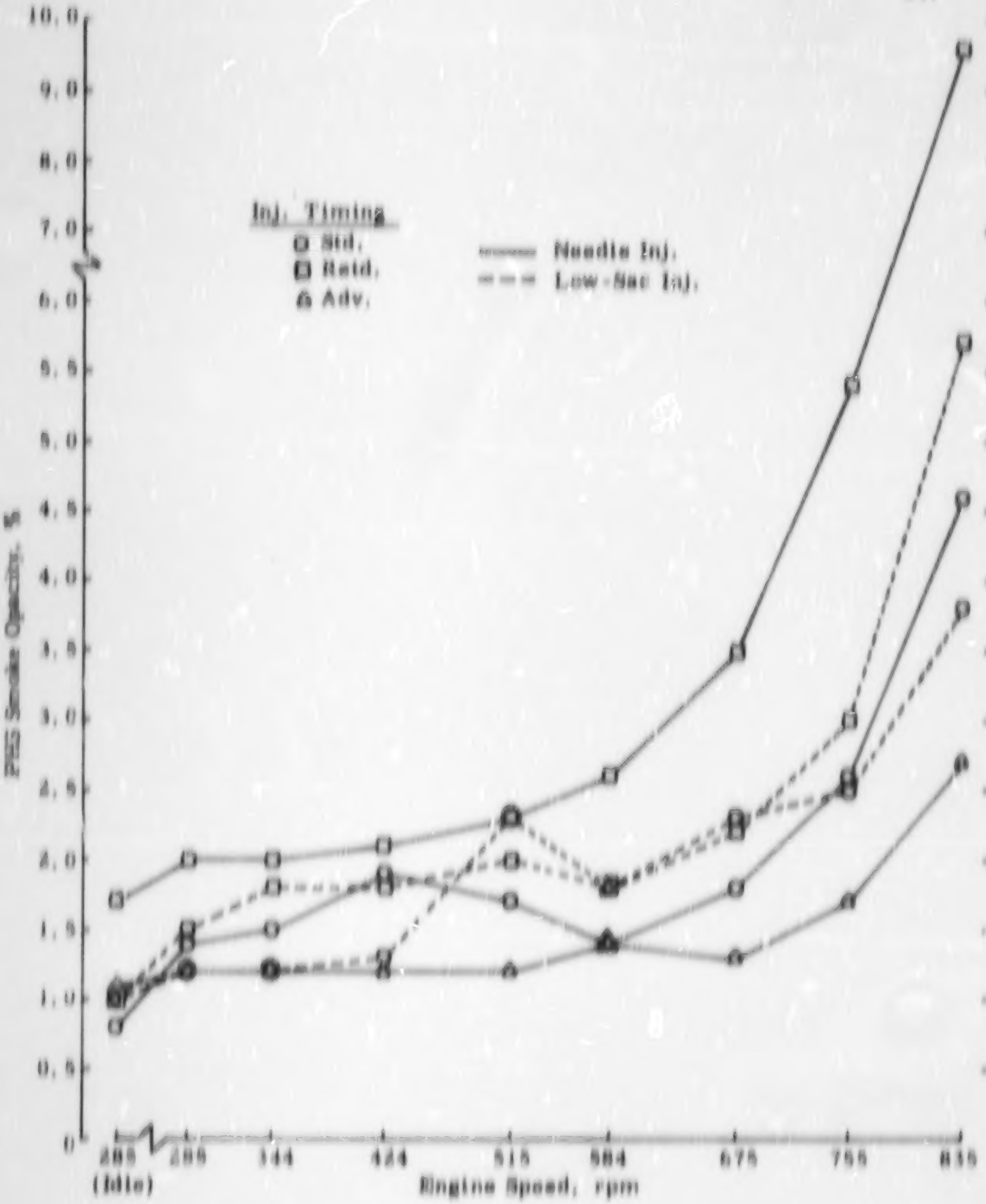


FIGURE 11. MODAL SMOKE OPACITY LEVELS FOR NEEDLE-VALVE AND LOW-SAC INJECTORS AT STANDARD AND NON-STANDARD TIMING

sufficient to reduce smoke opacity to 5 to 6 percent, which is the nominal smoke level for the needle-valve injectors at standard timing. An extra mode, featuring the derated power condition, was performed at the end of two of the tests made with retarded injection timing. The data thus obtained were substituted in place of the original mode 10 data in the computer program and the computations performed again. Only the G. E. line haul weight factors were used in this second set of computations, as the ATSF schedule attaches zero weight to the notch 8 position. The computer printouts for these two tests are also contained in Appendix B, Tables B-47 and B-48. The pertinent data from the printouts are summarized below in Table 6.

TABLE 6. EFFECT OF DERATING ON EMISSIONS, SMOKE AND POWER--NEEDLE-VALVE INJECTORS AT RETARDED TIMING

Cycle Composite Emissions

BSHC		BSCO		BSNO$_x$	
Normal	Derate	Normal	Derate	Normal	Derate
1.041	1.312	12.500	7.939	7.326	7.513

Notch 8 (Mode 10) Smoke, Emissions, and Power

Smoke, %		BSHC		BSCO		BSNO$_x$	
Normal	Derate	Normal	Derate	Normal	Derate	Normal	Derate
10.0	5.5	0.88	1.20	14.52	9.30	6.93	7.12

Power, Bhp		FSHC		FSCO		FSNO$_x$	
Normal	Derate	Normal	Derate	Normal	Derate	Normal	Derate
201	176	1.89	2.57	31.10	19.42	14.84	14.86

It can be seen that, besides the desired reduction in smoke opacity, derating produced slightly higher BSHC and BSNO$_x$ and much lower BSCO both on a cycle composite and modal basis. This same trend holds for the fuel specific quantities. The principal influences on these brake specific and fuel specific quantities are, of course, the 12 percent lower brake horsepower and 10 percent lower fuel rate of the derated condition. In summary, derating in notch 8 is a simple and effective method of obtaining the benefits of retarded timing of the needle injectors without the penalty of increased smoke opacity. Whether this amount of derating is desirable from an operations standpoint is another matter.

Retarded timing also caused smoke opacity associated with the low-sac injectors to increase somewhat over baseline (Table 7 and Figure 11).

However, the baseline (standard timing) opacities were so low that even the increased values were not excessive. Maximum opacity was less than six percent in notch 8; therefore, no tests were conducted with engine power derated in that position.

The average modal brake specific and fuel specific emissions for the needle injectors at standard, advanced, and retarded timing are presented in Table C-2 and illustrated in Figures C-7 through C-12 of Appendix C. Note that the BSHC (Figure C-7) was reduced principally in the first two notch positions by nonstandard timing, with less improvement noted in the later notches. Brake specific CO (Figure C-8) was lowered in the first two notches by retarded timing, but was somewhat increased in the higher-power conditions. The effect of timing on $BSNO_x$ is evident in every notch position (Figure C-9). The modal fuel specific emissions show the same relative trend as the brake specific quantities. It should be mentioned that the idle fuel rate was subject to some fluctuation; hence, there are some slight anomalies between the fuel specific emissions at idle and those for the eight notch positions.

Modal brake specific and fuel specific quantities for the low-sac injectors at standard and retarded timing are given in Table C-3 and shown in Figures C-13 through C-16 in Appendix C. Brake specific HC values (Figure C-13) are very close and show a distinct difference only in the last three notch positions (675 to 835 rpm). Similarly, BSCO (Figure C-13, also) differs significantly only in the last four notch positions. However, $BSNO_x$ (Figure C-14) was lower at every test point for retarded timing. Fuel specific HC and CO (Figure C-15) and NO_x (Figure C-16) again show the same general trends and the same relative differences as the corresponding brake specific quantities.

In summary, it is possible to obtain a substantial reduction in NO_x by retarding injection 4° from the standard setting. The percent reduction in NO_x was greatest for the needle injectors, which produced less NO_x than the low-sac injectors at standard timing. Retarded timing produced slightly less HC, but more smoke and CO in notch positions 5 through 8. Smoke opacity was judged to be a problem only for the needle injectors and the notch 8 condition. A slight power derating in this notch position appears to alleviate the problem. On the whole, engine power at all points of the test cycle was not adversely affected by retarded timing.

C. Effect of Water Induction on Emissions--Needle-Valve and Low-Sac Injectors at Standard Timing

Tests were conducted with needle-valve and low-sac injectors, using various rates of water induction (inlet air humidification). Water rates equal to 25, 50, 75, and 100 percent of the modal fuel flow mass were used. The cycle composite brake specific emissions are summarized in Table 9 for both types of injectors. The corresponding computer printouts appear

TABLE 9. CYCLE COMPOSITE BRAKE SPECIFIC EMISSIONS FOR NEEDLE-VALVE AND LOW-SAC INJECTORS, STANDARD TIMING, AND WATER INDUCTION

Injectors	Water Induction, %*	BSHC	BSCO	$BSNO_x$	$BSHC+BSNO_x$
		ATSF Weight Factor Schedule			
Needle	0	4.553	4.139	19.562	24.115
	25	2.784	3.018	17.711	20.495
	50	2.389	3.286	15.862	18.251
	75	1.814	4.881	15.023	16.837
	100	2.312	2.847	16.777	19.090
Low-Sac	0	1.837	2.702	22.563	24.400
	25	1.519	2.164	21.071	22.590
	50	1.655	2.490	20.508	22.164
	75	2.196	2.306	20.210	22.406
	100	2.199	3.426	19.914	23.113
		G.E. Weight Factor Schedule			
Needle	0	1.106	10.568	9.823	10.929
	25	0.897	10.240	9.193	10.090
	50	0.843	10.251	8.410	9.254
	75	0.736	10.210	7.622	8.358
	100	0.654	11.556	8.549	9.203
Low-Sac	0	0.655	7.281	13.045	13.700
	25	0.560	7.744	11.965	12.524
	50	0.562	6.999	11.353	11.914
	75	0.708	6.728	11.026	11.733
	100	0.734	8.164	10.802	11.536

---

*Percent of fuel flow mass per mode.

as Tables B-49 through B-88 of Appendix B.

Figures 12 and 13 illustrate the test results for the needle injectors. It is readily seen that the induction of more water (as percent of fuel flow mass) caused the BSHC and $BSNO_x$ to steadily decrease from the corresponding baseline (0 percent water) values, until 100 percent water rate was reached. At this point the BSHC and $BSNO_x$ went up, but the resulting values were still below baseline. Hence, the 75 percent water rate was optimum for the reduction of HC and NO_x. These reductions were noted regardless of the weight factor schedule used in the computations, though the magnitude of the reductions was different. Thus, at 75 percent water rate, cycle composite BSHC was 60 percent lower when the ATSF switch schedule was used and about 33 percent lower for the G. E. line haul schedule, while $BSNO_x$ was about 23 percent lower for both schedules.

Cycle composite BSCO was also affected by the rate of water induction, but the changes produced were highly dependent on the weight factors used in the calculations. Thus, in Figure 13, note that when the ATSF schedule was used, BSCO was highest for the 75 percent water rate and lowest for the 100 percent flow rate. But when G. E. weight factors were used, BSCO was highest for the 100 percent rate and lowest (and approximately equal) at the 25, 50, and 75 percent water rates.

Figures 14 and 15 depict the average cycle composite values for the low-sac injectors. Brake specific HC was lowered by the 25 and 50 percent water rates and increased by the other two induction rates. Brake specific CO showed little or no improvement in these tests. However, $BSNO_x$ steadily decreased as the water rate was increased, so that the 100 percent rate produced the least NO_x. The total reduction from the baseline (0 percent water) value was 12 and 17 percent for the ATSF and G. E. weighting schedules, respectively. These are smaller reductions, percentage-wise, than were found to occur with the needle injectors.

Modal smoke opacity for both types of injectors is presented in Table 10 and illustrated in Figure 16 (needle) and Figure 17 (low-sac). It is evident that water induction did not lead to excessive smoke in any instance. In this regard, water induction was superior to retarded injection timing, at least as far as the needle injectors were concerned.

Average modal brake specific and fuel specific emissions for needle injectors are given in Table C-4 and shown in Figures C-17 through C-22 of Appendix C. Water induction resulted in lower BSHC and $BSNO_x$ in almost every mode, and the general efficacy of the 75 percent water rate is evident. The effect on BSCO is not so clearly defined.

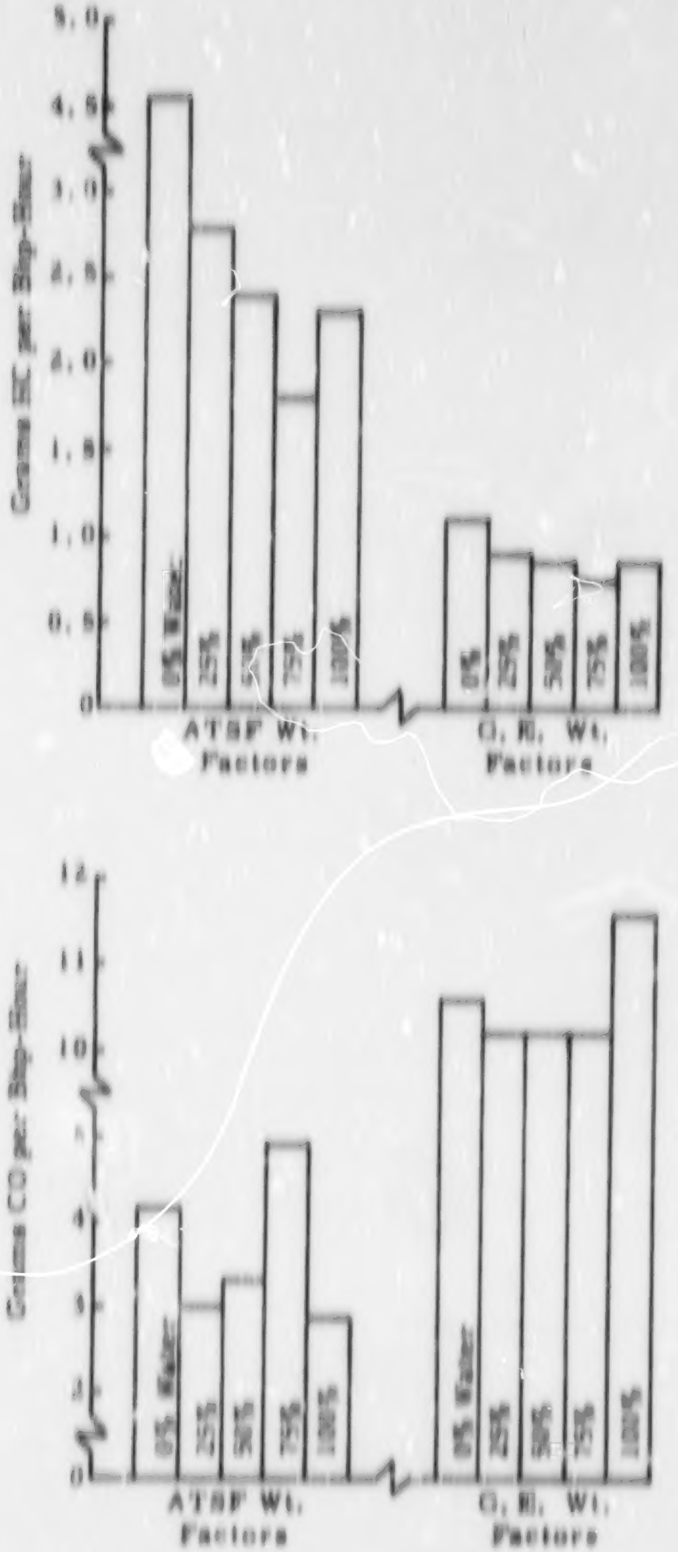


FIGURE 12. CYCLE COMPOSITE BRAKE SPECIFIC HC AND CO FOR VARIOUS WATER INDUCTION RATES: NEEDLE INJECTORS AT STANDARD TIMING

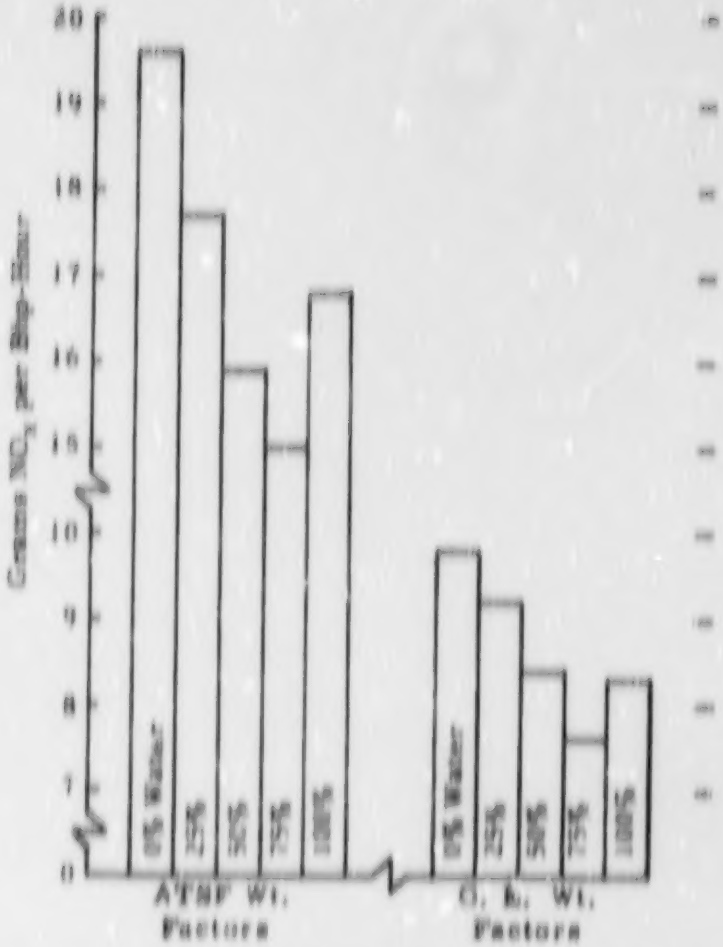
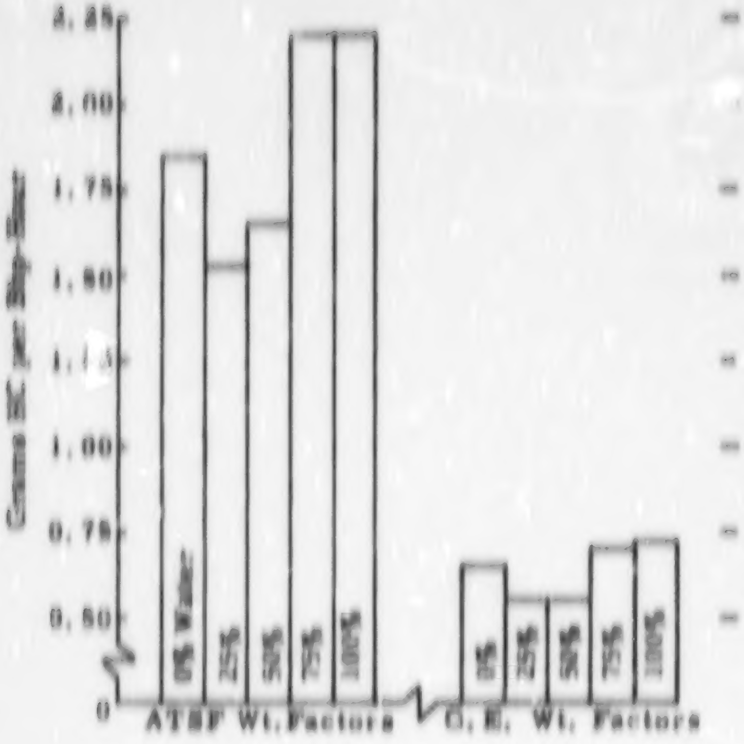


FIGURE 13. CYCLE COMPOSITE BRAKE SPECIFIC NO_x FOR VARIOUS WATER INDUCTION RATES--NEEDLE INJECTORS AT STANDARD TIMING



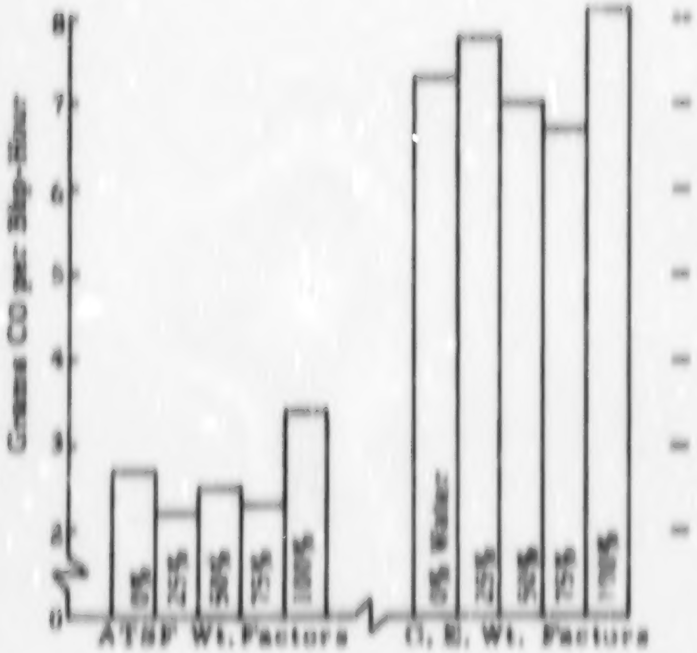


FIGURE 14. CYCLE COMPOSITE BRAKE SPECIFIC HC AND CO FOR VARIOUS WATER INDUCTION RATES--LOW-SAC INJECTORS AT STANDARD TIMING

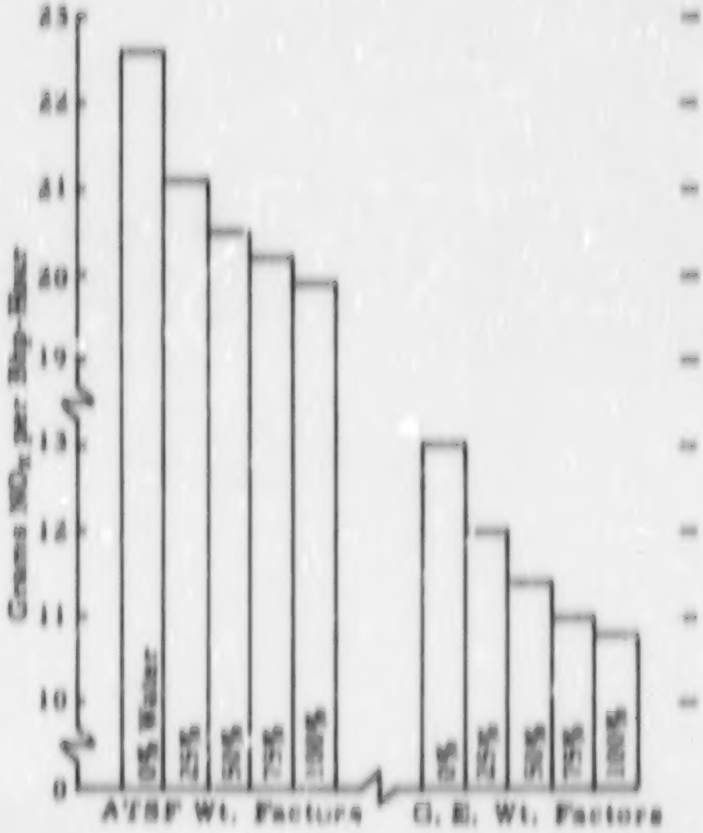


FIGURE 15. CYCLE COMPOSITE BRAKE SPECIFIC NO_x FOR VARIOUS WATER INDUCTION RATES--LOW-SAC INJECTORS AT STANDARD TIMING

TABLE 10. MODAL SMOKE OPACITY FOR NEEDLE-VALVE AND LOW-SAC INJECTORS, STANDARD TIMING, AND WATER INDUCTION

Mode	Notch Position	Engine Speed, rpm	PHS Smoke Opacity, %				
			0% Water*	25%*	50%*	75%*	100%*
	Needle Injectors						
1, 6, 11	Low Idle	285	0, 8	1, 0	0, 8	0, 9	1, 4
2	1	285	1, 4	1, 5	1, 2	1, 5	1, 3
3	2	344	1, 5	1, 0	1, 0	1, 2	1, 3
4	3	424	1, 9	1, 0	0, 8	1, 0	1, 5
5	4	515	1, 7	1, 2	1, 0	1, 0	1, 5
7	5	584	1, 4	1, 2	1, 2	1, 2	1, 5
8	6	675	1, 8	1, 3	1, 3	1, 7	2, 0
9	7	755	2, 6	2, 5	2, 3	2, 8	3, 0
10	8	835	4, 6	4, 7	5, 2	5, 8	6, 0
	Low Sac Injectors						
1, 6, 11	Low Idle	285	1, 0	1, 0	1, 1	1, 1	1, 0
2	1	285	1, 2	1, 0	1, 0	1, 2	1, 2
3	2	344	1, 2	1, 5	1, 0	1, 2	1, 5
4	3	424	1, 3	1, 5	1, 0	1, 2	1, 5
5	4	515	2, 3	2, 0	2, 0	2, 0	2, 8
7	5	584	1, 8	1, 5	1, 8	2, 0	2, 0
8	6	675	2, 3	1, 5	1, 8	2, 2	2, 2
9	7	755	2, 9	1, 8	2, 5	2, 2	2, 2
10	8	835	3, 8	3, 3	3, 5	4, 8	4, 5

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*Percent of fuel flow mass per mode.

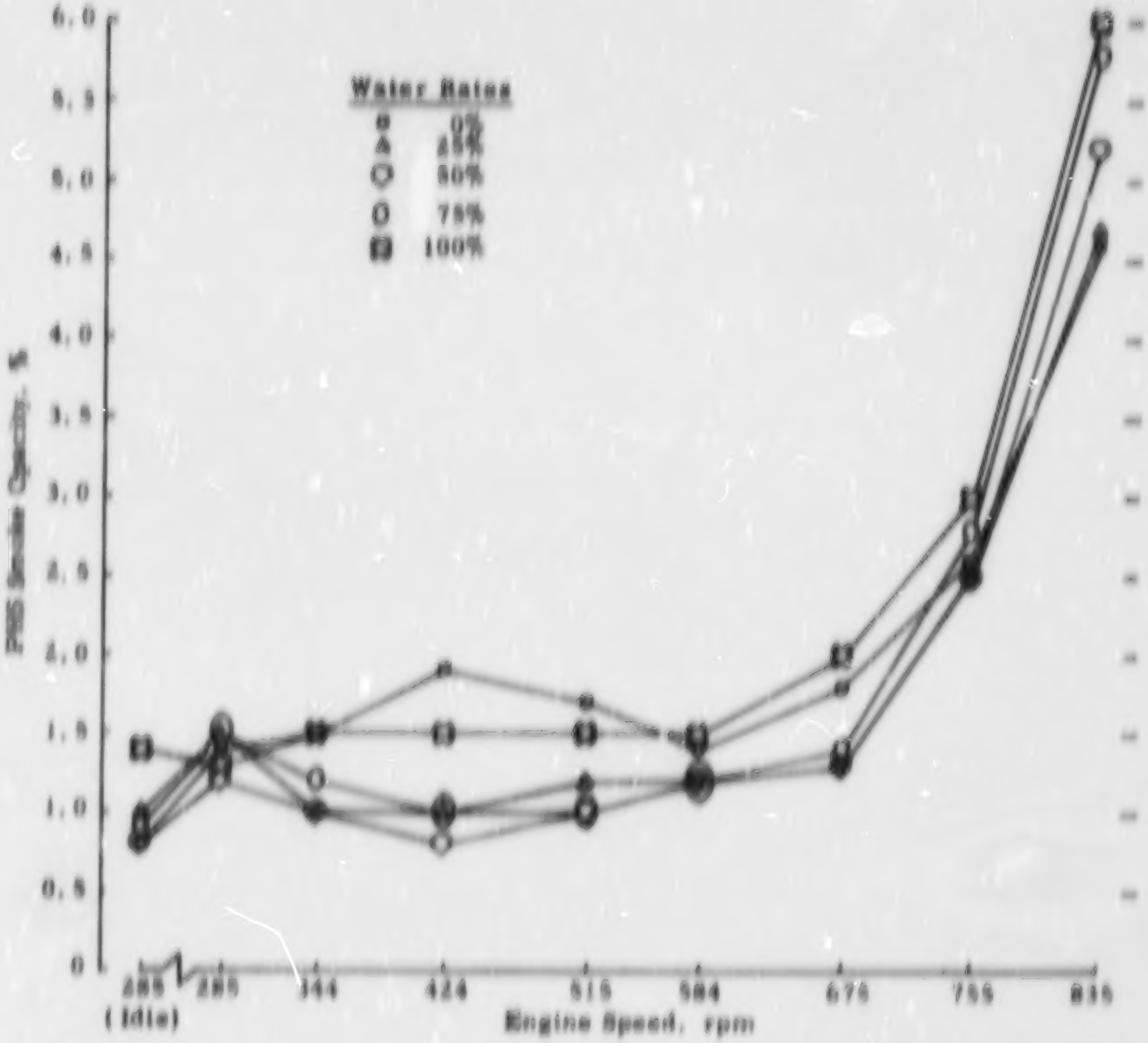

FIGURE 16. MODAL SMOKE OPACITY LEVELS FOR VARIOUS WATER INDUCTION RATES--NEEDLE-VALVE INJECTORS AT STANDARD TIMING

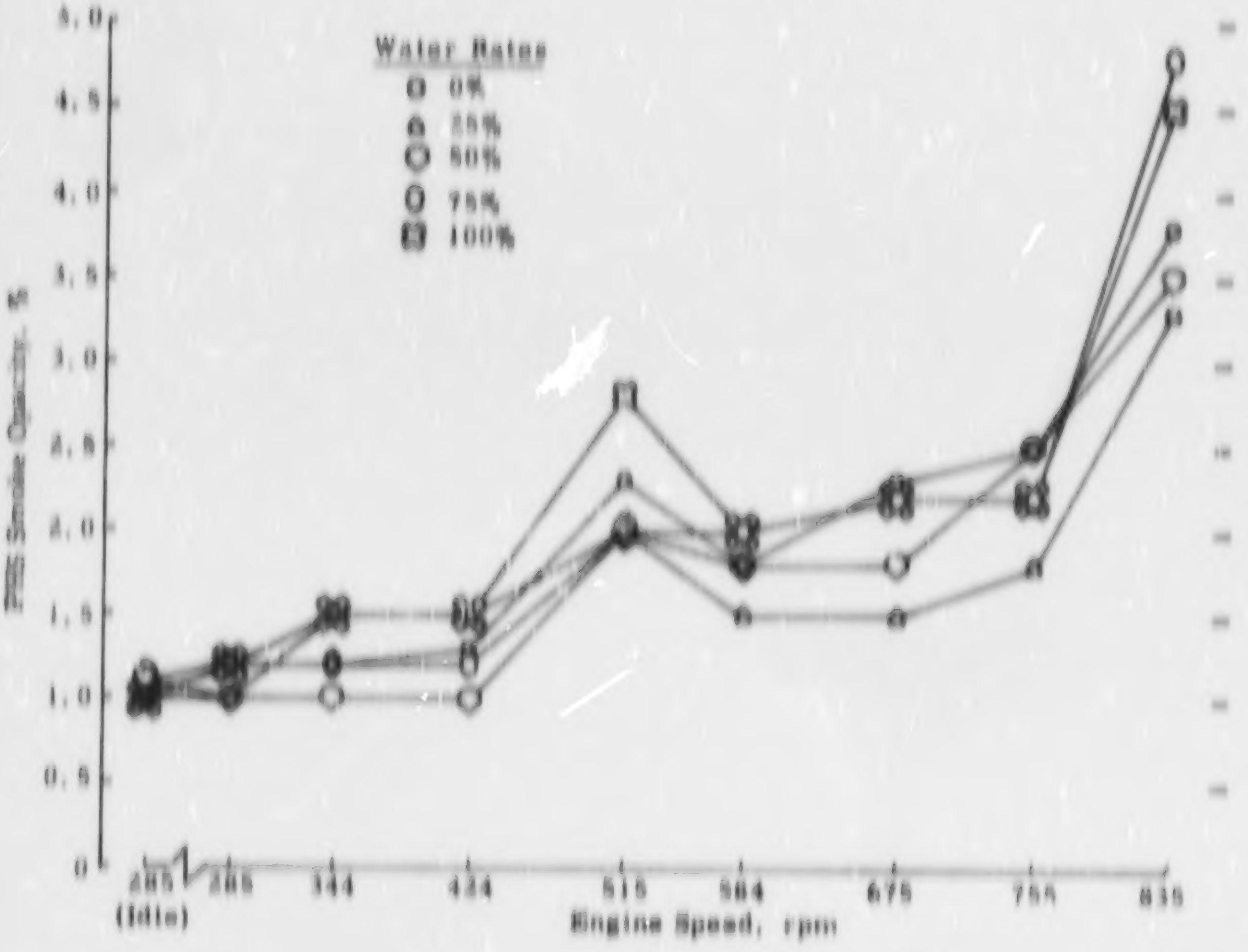

FIGURE 17. MODAL SMOKE OPACITY LEVELS FOR VARIOUS WATER INDUCTION RATES--LOW-SAC INJECTORS AT STANDARD TIMING

The modal brake specific and fuel specific data for low-sac injectors are given in Table C-5 and illustrated by Figures C-23 through C-27 of Appendix C. The effect of the 100 percent water rate is apparent; HC and CO are higher at nearly every test point, while NO_x is lower in the higher notch positions. However, the 75 percent rate was very nearly as effective as the 100 percent rate in reducing NO_x.

In summary, water induction proved effective in reducing NO_x, but the higher water rates resulted in slight increases in HC and CO. The observed reductions in NO_x were less than that which occurred with retarded injection timing. However, smoke opacity was not increased substantially by water induction and no derating of engine power was necessary. In fact, engine power appeared to experience a slight increase with water induction, possibly due to cooling of the intake air.

Before concluding this discussion of water induction as a control method, it should be mentioned that rather large quantities of water were found at the bottom of the engine air box following a series of tests. This water, usually several gallons worth, evidently passed through the blower without being thoroughly mixed with the intake air. It is not known if this problem could be solved by using a different, possibly more efficient, method of water atomization. It is also not known if a full-size, in-service locomotive engine would generate air box temperatures sufficiently high enough to vaporize this water as it collects.

D. Effect of Water Induction on Emissions - Needle-Valve and Low-Sac Injectors at Retarded Timing

These tests involved a combination of two control methods that, when used separately, generally resulted in substantial reductions of NO_x. For tests with needle injectors, water induction rates of 25, 50, and 75 percent of fuel flow mass were used. The 100 percent water rate was not used since, as mentioned previously, there was no further reduction in NO_x above the 75 percent rate with standard timing. With low-sac injectors, only the 100 percent water rate, which was most effective at standard timing, was used. The computer printouts for these tests appear in Appendix B as Tables B-89 through B-104.

Cycle composite emissions for the needle injectors are summarized in Table 11 and shown in Figures 18 and 19. Several points of interest are immediately obvious. First, water induction did not result in significant reductions in BSHC when injection timing was retarded. This is in contrast to the reductions observed for water induction in conjunction with standard timing. Second, the combination of water induction and retarded

TABLE 11. CYCLE COMPOSITE BRAKE SPECIFIC EMISSIONS FOR NEEDLE-VALVE INJECTORS, STANDARD AND RETARDED TIMING, AND WATER INDUCTION

Water Induction, %*	Injection Timing	BSHC	BSCO	$BSNO_x$	$BSHC+BSNO_x$
		ATSF Weight Factor Schedule			
0	Std.	4.533	4.139	19.582	24.115
	Retd.	3.526	3.988	13.226	16.753
25	Std.	2.784	3.018	17.711	20.495
	Retd.	2.792	2.748	12.030	14.822
50	Std.	2.389	3.286	15.862	18.251
	Retd.	2.668	3.892	11.198	13.866
75	Std.	1.814	4.881	15.023	16.837
	Retd.	2.666	3.673	10.953	13.620
		G.E. Weight Factor Schedule			
0	Std.	1.106	10.568	9.823	10.[illegible]
	Retd.	1.041	12.500	7.326	8.366
25	Std.	0.897	10.240	9.193	10.090
	Retd.	1.460	13.954	6.024	7.484
50	Std.	0.843	10.281	8.410	9.254
	Retd.	1.218	15.122	5.630	6.848
75	Std.	0.736	10.210	7.622	8.358
	Retd.	1.182	14.752	5.310	6.492

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*Percent of fuel flow mass per mode.

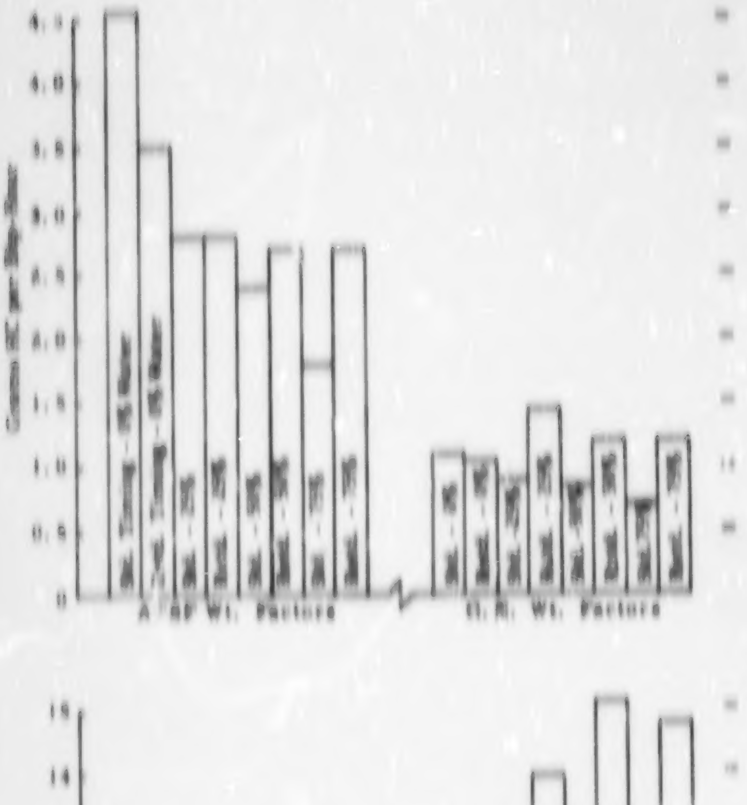

FIGURE 15. CYCLE COMPOSITE BRAKE SPECIFIC HC AND CO FOR VARIOUS WATER INDUCTION RATES--NEEDLE-VALVE INJECTORS AT STANDARD AND RETARDED TIMING

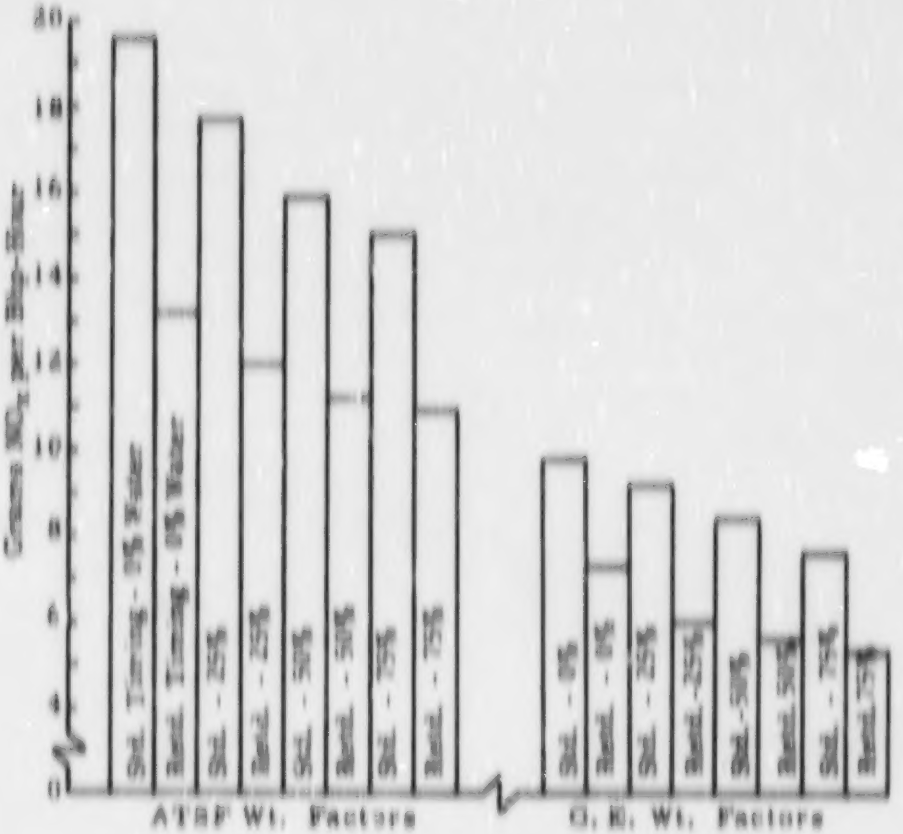

FIGURE 19. CYCLE COMPOSITE BRAKE SPECIFIC NO_x FOR VARIOUS WATER INDUCTION RATES--NEEDLE-VALVE INJECTORS AT STANDARD AND RETARDED TIMING

timing had an adverse effect on BSCO, especially when the cycle composite values were computed with the G. E. weight factor schedule, with its heavy emphasis on the notch 8 position. Note that the addition of water produced almost no change in BSCO when standard timing was used. However, water induction produced much higher BSCO when injection was retarded. Third, water induction produced a reduction in $BSNO_x$ beyond that produced by retarded timing alone. Note the stepwise reductions in $BSNO_x$ as produced by successively higher water rates for both standard and retarded injection timing (Figure 19). However, water induction was not quite as effective with retarded timing as with standard timing. In all, going from standard timing without water to retarded timing with water produced a 44 percent reduction in $BSNO_x$ for the ATSF cycle and a 46 percent reduction for the G. E. cycle. Over one-half of these reductions (32 and 25 percent, respectively) were due to retarded timing, alone.

Figures 20 and 21 illustrate the cycle composite results for low-sac injectors (Table 12, top). Brake specific HC remained almost constant when water induction was used with retarded timing, while BSCO decreased slightly for the ATSF cycle and increased moderately for the G. E. cycle. The $BSNO_x$ values were reduced substantially by using water with retarded timing. Reductions of 40 percent and 47 percent, respectively, were noted in the values for the ATSF and G. E. cycles when standard timing without water was changed to retarded timing and the 100 percent water rate. Of these reductions, over one-half (27 and 28 percent) was again due to retarded timing, alone.

Modal smoke opacity for the tests with needle injectors is given in Table 13 and illustrated in Figure 22. Smoke opacity for low-sac injectors is contained in Table 12 (lower right-hand column) and shown in Figure 23. It can be seen that water induction, particularly at the higher flow rates, caused opacity to increase in the upper notch positions; however, only the smoke in notch 8 was cause for concern. Of course, the needle injectors produced more smoke than the low-sac units. Engine power derating was not tried, since it would probably not yield substantially different results from those discussed previously.

Modal brake specific and fuel specific emissions for the needle-valve injectors are contained in Appendix C, Table C-6 and Figures C-28 through C-33. Brake specific HC experienced a moderate increase in notch position 8, while $BSNO_x$ was reduced at all test points by water induction. Brake specific CO was increased by all three water rates in notches 5 to 8 (584 to 835 rpm), and this well-defined trend was not evident in tests involving water and standard timing. Modal fuel specific emissions follow these same trends in all notch positions.

TABLE 12. SUMMARY OF CYCLE COMPOSITE AND MODAL EMISSIONS DATA FOR LOW-SAC INJECTORS, RETARDED TIMING, AND OPTIMUM WATER INDUCTION RATE (100% of Fuel Flow Mass per Mode)

Water Induction, %*	Injection Timing	Cycle Composite Gaseous Emissions BSHC	BSCO	BSNO$_x$	BSHC + BSNO$_x$
		ATSF Weight Factor Schedule			
0	Std.	1.837	2.702	22.563	24.400
	Retd.	1.715	3.194	16.572	18.287
100	Std.	2.199	3.426	19.914	22.113
	Retd.	2.182	2.579	13.530	15.711
		C.E. Weight Factor Schedule			
0	Std.	0.655	7.281	13.045	13.700
	Retd.	0.605	9.783	9.186	9.791
100	Std.	0.734	8.164	10.802	11.536
	Retd.	0.736	10.846	6.881	7.617

Mode	Engine Speed, rpm	Modal Gaseous Emissions and Smoke Opacity (Retd. Timing) Grams/Bhp-Hour HC	CO	NO$_x$	Grams/Pound of Fuel HC	CO	NO$_x$	PHS Smoke Opacity, %
				0% Water Induction*				
1, 6, 11	285	-	-	-	3.86	5.08	29.33	1.0
2	285	0.71	1.81	12.75	1.28	3.24	22.92	1.2
3	344	0.61	1.25	11.23	1.22	2.49	22.39	1.2
4	424	0.46	0.69	11.41	1.03	1.55	25.72	1.3
5	515	0.43	0.44	12.87	0.99	1.03	29.84	2.1
7	584	0.42	0.56	13.82	0.99	1.31	32.30	1.8
8	675	0.49	1.04	13.61	1.14	2.41	31.47	2.3
9	755	0.54	3.28	13.16	1.24	7.56	30.27	2.5
10	835	0.60	8.86	12.19	1.32	19.75	27.20	3.8
				100% Water Induction*				
1, 6, 11	285	-	-	-	6.02	6.38	25.02	1.0
2	285	1.02	1.58	6.96	2.00	3.10	13.70	1.2
3	344	0.86	1.20	6.34	1.72	1.78	12.68	1.2
4	424	0.58	0.80	6.40	1.31	1.28	14.54	1.8
5	515	0.50	0.52	7.63	1.20	1.14	18.36	2.8
7	584	0.46	1.38	7.76	1.12	3.36	18.76	2.5
8	675	0.52	2.41	7.28	1.23	5.75	17.36	2.8
9	755	0.60	5.58	6.96	1.38	12.82	15.99	4.5
10	835	0.66	13.20	6.24	1.47	29.34	13.85	7.5

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*Percent of fuel flow mass per mode.

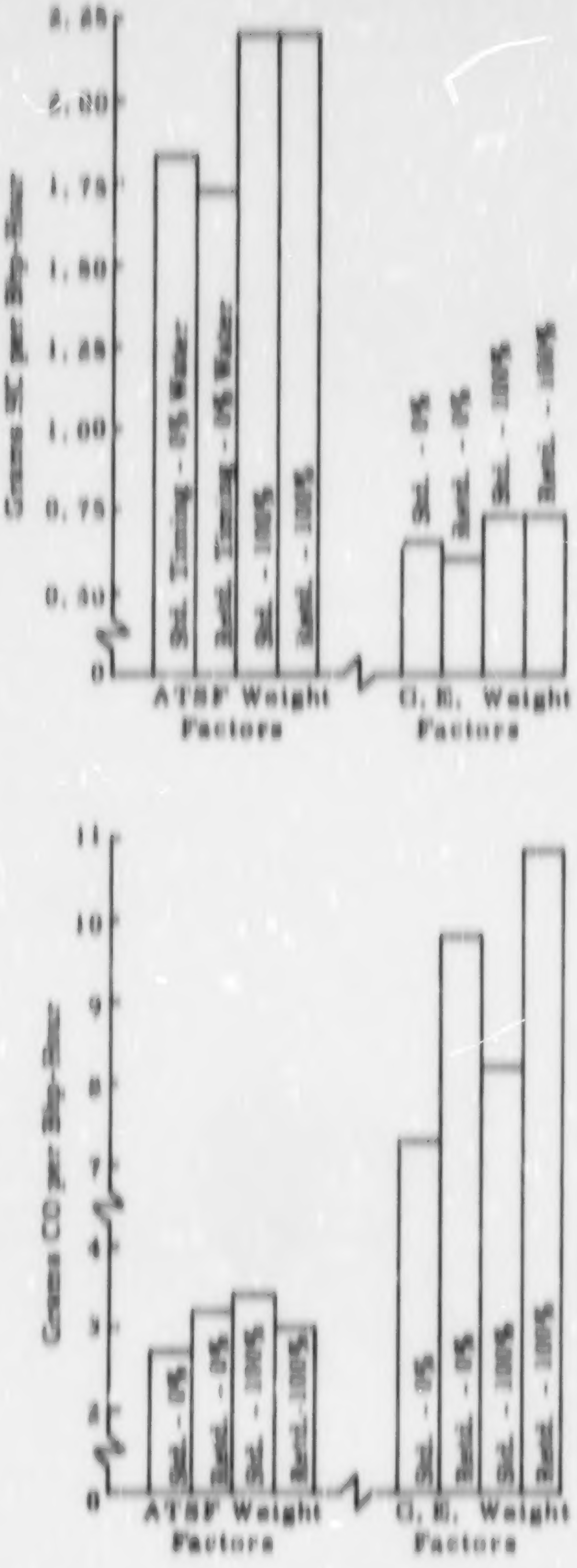

FIGURE 20. CYCLE COMPOSITE BRAKE SPECIFIC HC AND CO FOR OPTIMUM WATER INDUCTION RATE--LOW-SAC INJECTORS AT STANDARD AND RETARDED TIMING

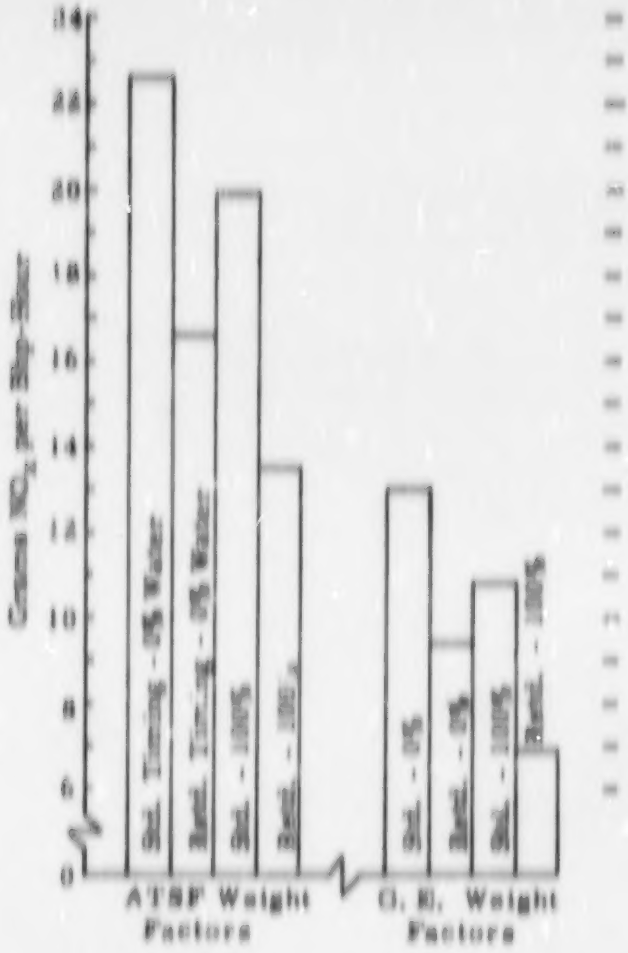

FIGURE 21. CYCLE COMPOSITE BRAKE SPECIFIC NO$_x$ FOR OPTIMUM WATER INDUCTION RATE--LOW-SAC INJECTORS AT STANDARD AND RETARDED TIMING

TABLE 13. MODAL SMOKE OPACITY FOR NEEDLE-VALVE INJECTORS, RETARDED TIMING, AND WATER INDUCTION

Mode	Notch Position	Engine Speed, rpm	PHS Smoke Opacity, % 0% Water*	25%*	50%*	75%*
1, 6, 11	Low Idle	285	1.8	1.4	1.2	1.2
2	1	285	2.0	2.2	2.0	2.2
3	2	344	2.0	1.8	1.5	1.5
4	3	424	2.1	1.8	2.0	2.0
5	4	515	2.3	2.0	2.4	2.5
7	5	584	2.8	2.5	2.5	2.8
8	6	675	3.5	3.5	3.5	4.0
9	7	755	5.5	5.8	5.8	6.2
10	8	835	10.0	10.8	12.0	12.0

*Percent of fuel flow mass per mode

Similar data from the tests with low-sac injectors are presented in Table 12 (bottom) and Figures C-34 through C-38 of Appendix C. It is evident that the 100 percent water rate caused HC and CO to increase slightly, and NO_x to decrease significantly, in almost every test mode.

E. Effect of Air Box Bleed on Emissions--Needle-Valve and Low-Sac Injectors at Standard Timing

For these tests injectors were set to standard timing, and a set percentage of the scavenging air was vented from the engine air box at each mode of the test cycle. The amount of air vented was equal to 10, 20, 35, or 50 percent of the total air requirement of the engine for tests with needle injectors. Only the 20 and 35 percent bleed rates were tested with low-sac injectors.

Before proceeding to the analysis of the test results, it should be noted that the reduction of scavenging air can affect the brake specific emissions (both modal and cycle composite) in three ways. First, the mass of the exhaust gases is reduced by a percentage very nearly equal to that of the scavenging air reduction. Second, the concentrations of HC, CO, and/or NO_x may be increased or decreased by air box bleed. Either or both of these two factors produce a change in the mass flow (grams/hr) of the contaminants. Third, the power output of the engine is usually lowered by the reduction of scavenging air; hence, brake specific quantities will be increased by the decrease in horsepower. Fuel specific emissions are influenced by the first two factors, but not by the last, assuming that modal fuel flow mass is held constant from one series of tests to another. This was the case here, except that idle fuel rates were uncontrolled, i.e., allowed to experience normal fluctuations.

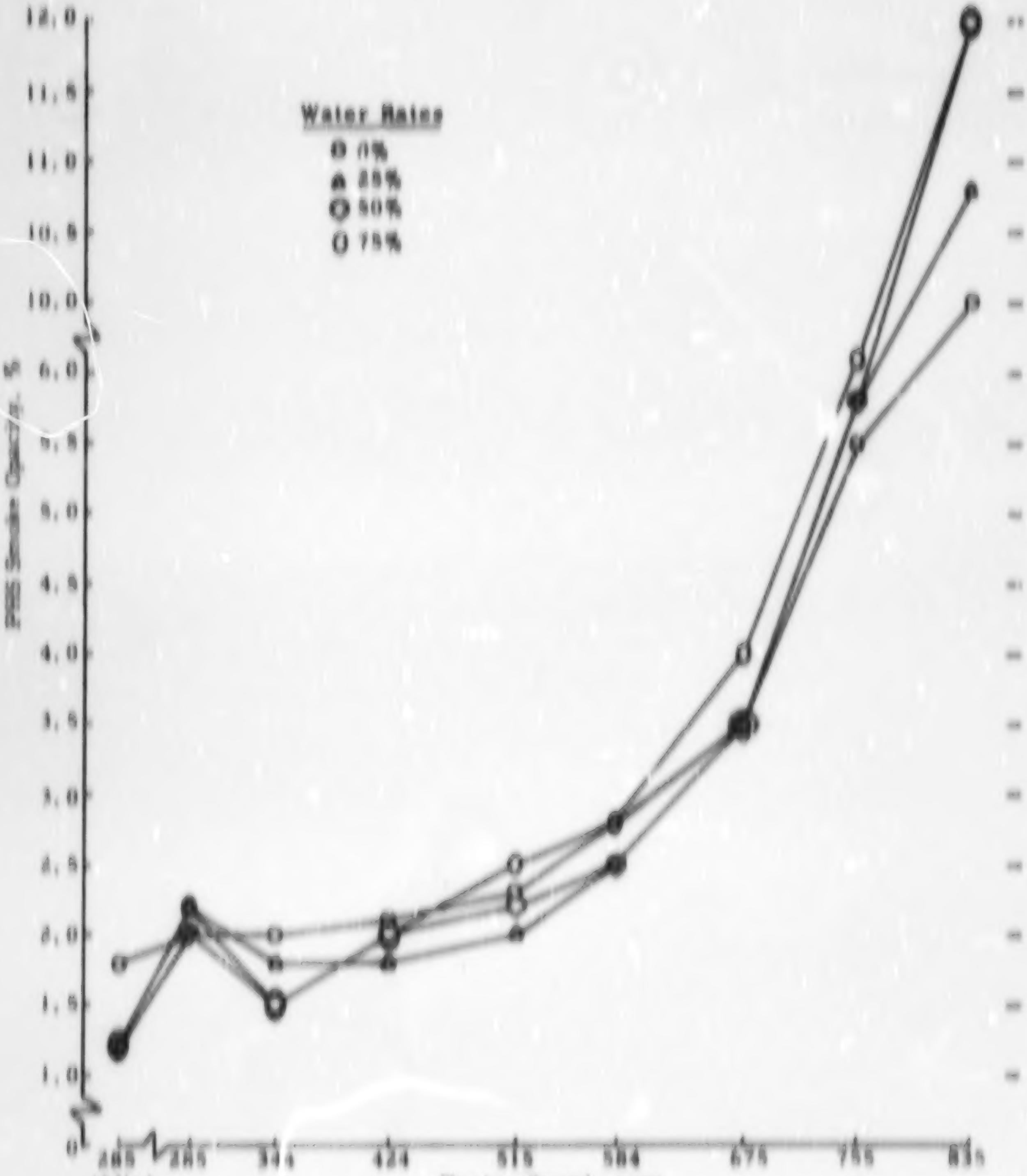

FIGURE 23. MODAL SMOKE OPACITY LEVELS FOR VARIOUS WATER INDUCTION RATES--NEEDLE-VALVE INJECTORS AT RETARDED TIMING

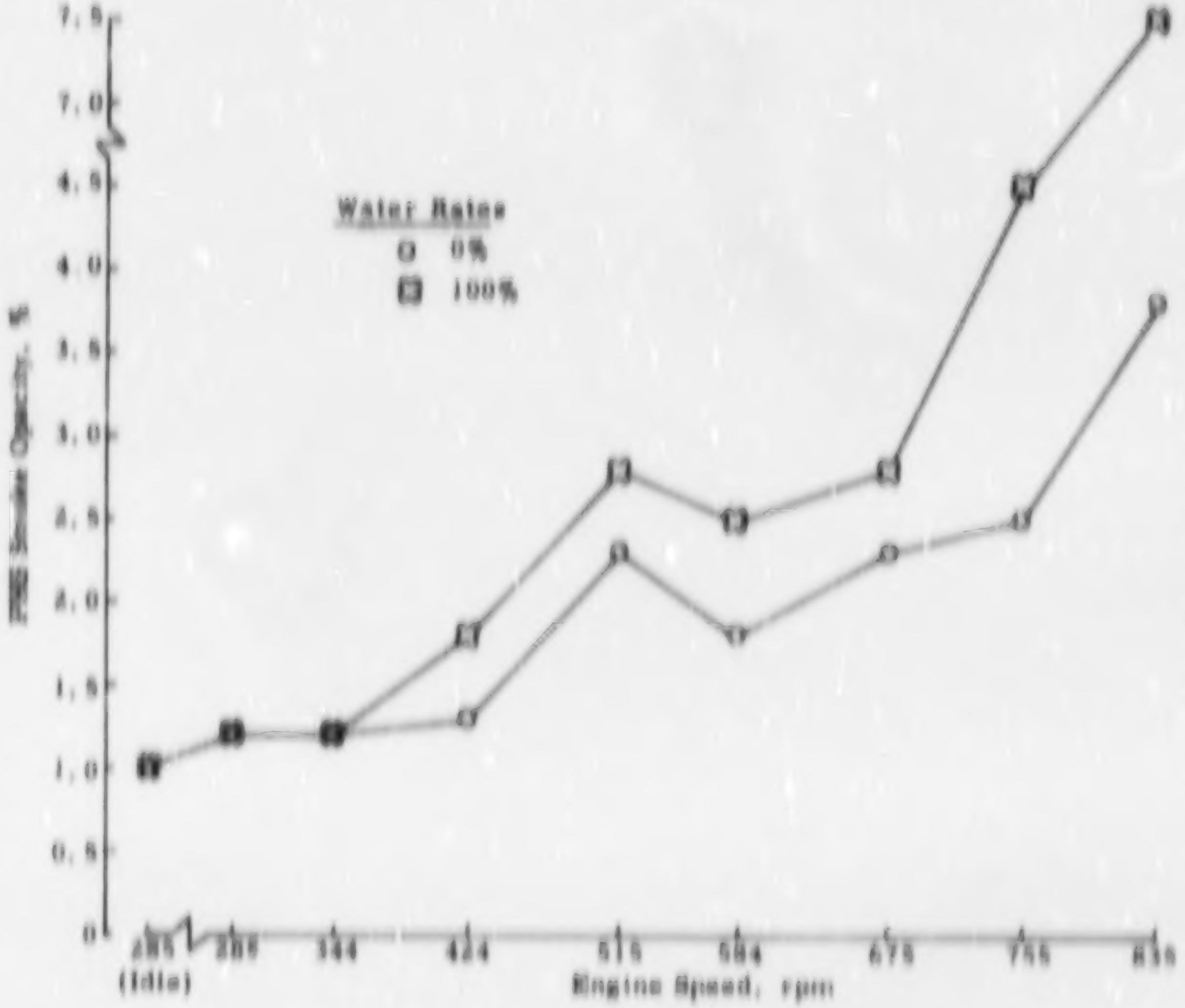

FIGURE 23. MODAL SMOKE OPACITY LEVELS FOR OPTIMUM WATER INDUCTION RATE--LOW-SAC INJECTORS AT RETARDED TIMING

In order to help keep the factor of emission concentrations in mind, a table and three figures are included to show the effect of air box bleed on modal concentrations of HC, CO, and NO_x.

The computer printouts for these tests are in Appendix B, Tables B-105 through B-112. Average cycle composite brake specific emissions are summarized in Table 14 and shown in Figures 24 and 25 (needle injectors) and Figures 26 and 27 (low-sac injectors). It is evident from Figure 24 that air box bleed with the needle injectors tended to reduce BSHC values, especially those computed with the ATSF weighting schedule. Brake specific CO, also computed with ATSF weight factors, was reduced somewhat by the 10, 20, and 35 percent bleed rates. However, all rates of air bleed caused the BSCO based on the G. E. line haul weight factors to increase over the baseline (0 percent bleed) value. Brake specific NO_x (Figure 25) was reduced under all test conditions, but in most cases the reductions were just approximately equal to the mass flow reduction produced by the air bleed.

For low-sac injectors, air box bleed increased BSHC in all but one instance (Figure 26, top), while BSCO increased in every case, even for the ATSF cycle (Figure 26, bottom). Brake specific NO_x was generally lower with air box bleed, but the observed reductions could mostly be attributed to the reduced mass flow of exhaust, though not to the same extent as for the needle injectors.

At this point in the analysis, it is of interest to look at the effect of air bleed on concentrations, since the behavior of these concentrations reflects, to a large extent, the behavior of the cycle composite quantities just discussed, as well as the modal brake specific and fuel specific values that will be discussed shortly.

Table C-7 and Figures C-39, C-40, and C-41 of Appendix C contain the concentrations for the needle injectors. Note that HC concentrations are generally lower at idle and notch 8, which are the most important points of the test cycle; i.e., they receive the greatest amount of weighting in the two weighting schedules used. The generally adverse effect of air box bleed on CO concentration is clearly evident. Idle concentrations were reduced by a small amount, but the overall result was very detrimental. However, the effect on concentrations of NO_x was favorable. There was only slight differences in the various idle concentrations, but beginning at notch 3 (434 rpm) the 50 percent bleed rate began producing appreciable reductions in NO_x. At the notch 8 position, the reduction from baseline (0 percent) concentration was approximately 30 percent. The 35 percent bleed was responsible for a reduction of about 20 percent in notch 8.

TABLE 14. CYCLE COMPOSITE BRAKE SPECIFIC EMISSIONS FOR NEEDLE-VALVE AND LOW-SAC INJECTORS, STANDARD TIMING, AND AIR BOX BLEED

Injectors	Air Box Bleed %*	BSHC	BSCO	$BSNO_x$	$BSHC + BSNO_x$
		ATSF Weight Factor Schedule			
Needle	0	4.553	4.139	19.562	24.115
	10	3.164	3.222	16.993	20.157
	20	2.460	2.611	14.901	17.362
	35	1.839	3.281	13.248	15.088
	50	2.133	6.456	10.893	13.026
Low-Sac	0	1.837	2.702	22.563	24.400
	10	-	-	-	-
	20	1.973	3.174	18.084	20.057
	35	1.310	9.184	13.681	14.992
	50	-	-	-	-
		G.E. Weight Factor Schedule			
Needle	0	1.106	10.568	9.823	10.929
	10	1.318	11.492	9.190	10.508
	20	0.846	14.106	8.210	9.056
	35	0.541	15.917	6.734	7.275
	50	0.382	20.052	5.038	5.421
Low-Sac	0	0.655	7.281	13.045	13.700
	10	-	-	-	-
	20	0.611	16.612	9.522	10.134
	35	0.339	17.258	7.151	7.490
	50	-	-	-	-

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*Percent of engine air flow mass requirement per mode.

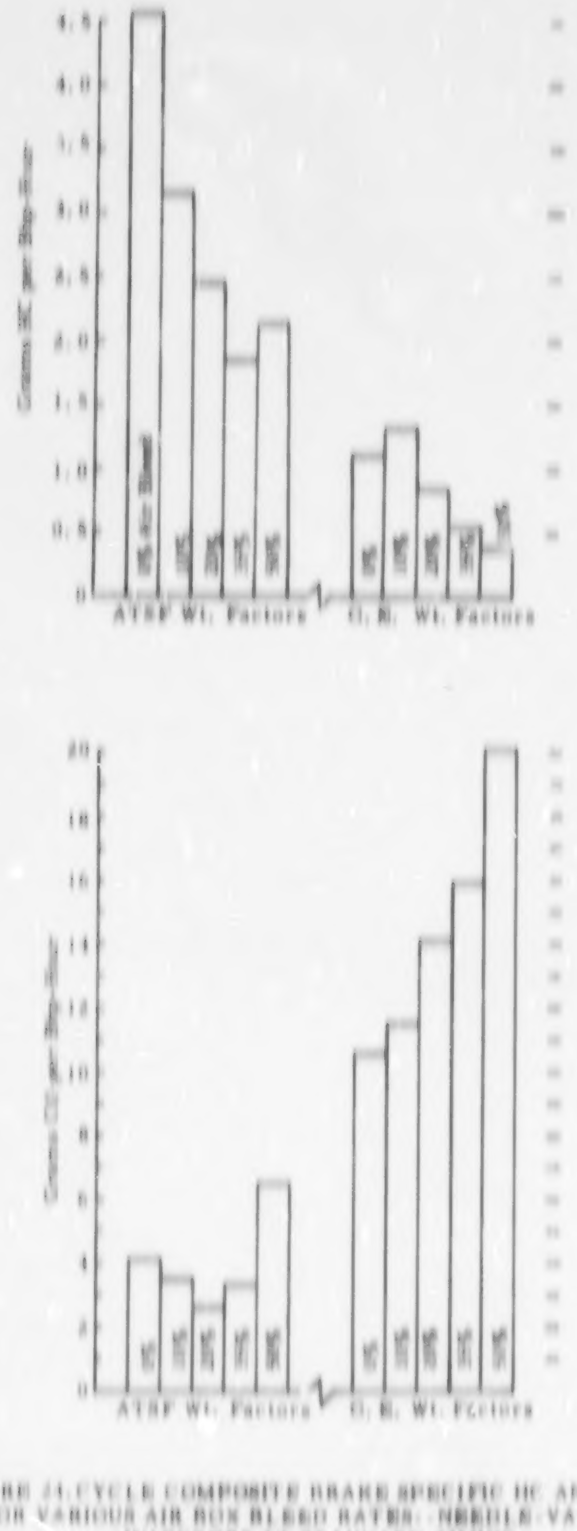

FIGURE 21. CYCLE COMPOSITE BRAKE SPECIFIC HC AND CO FOR VARIOUS AIR BOX BLEED RATES: NEEDLE-VALVE INJECTORS AT STANDARD TIMING

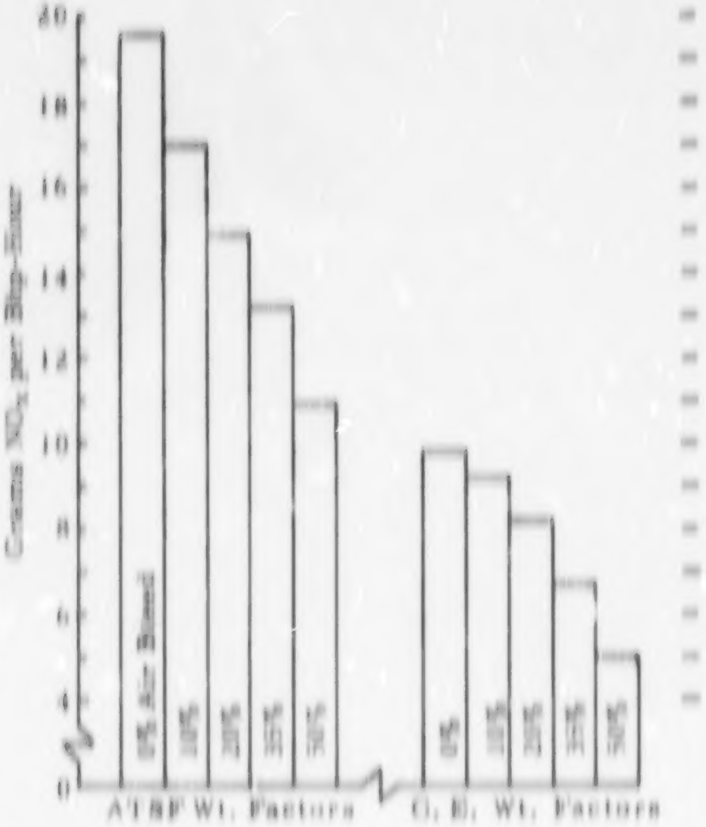

FIGURE 25. CYCLE COMPOSITE BRAKE SPECIFIC NO_x FOR VARIOUS AIR BOX BLEED RATES—NEEDLE-VALVE INJECTORS AT STANDARD TIMING

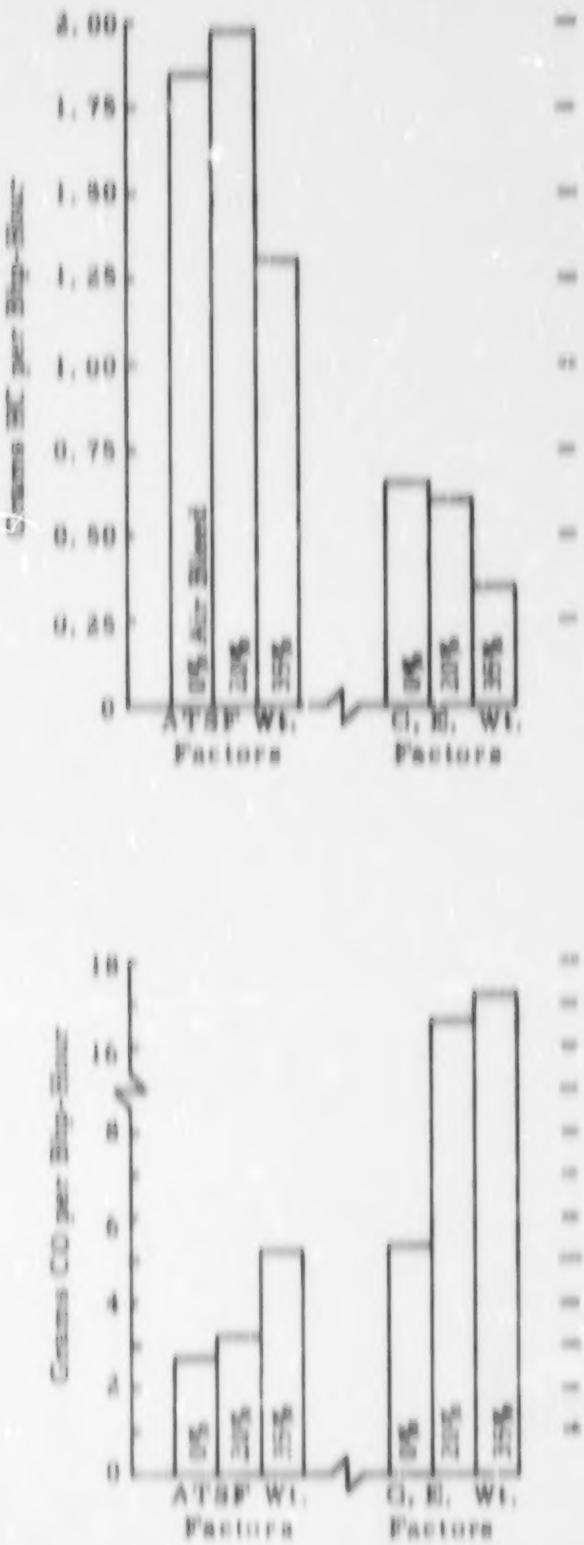

FIGURE 26. CYCLE COMPOSITE BRAKE SPECIFIC HC AND CO FOR VARIOUS AIR BOX BLEED RATES--LOW-SAC INJECTORS AT STANDARD TIMING

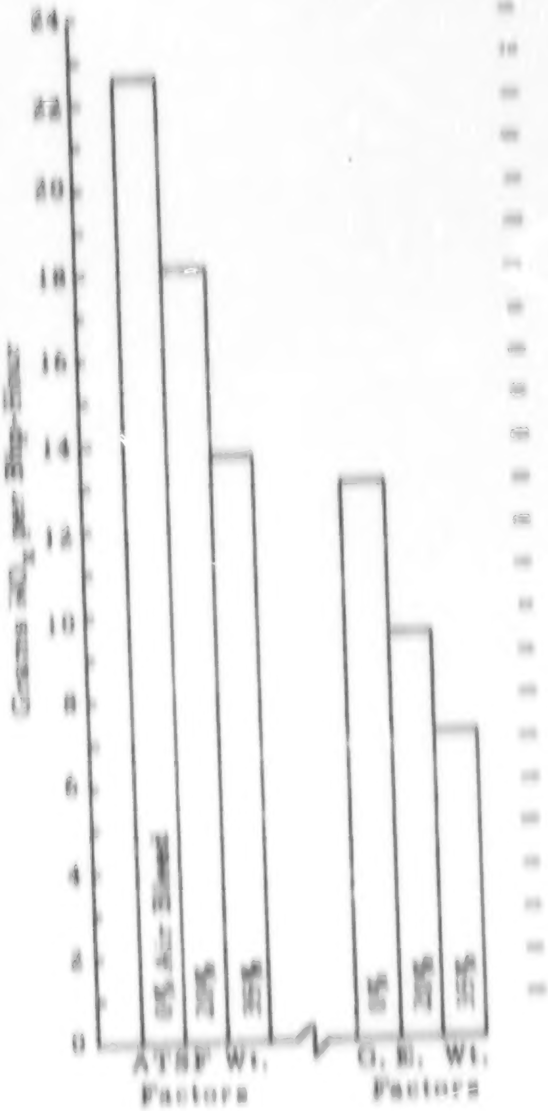

FIGURE 27. CYCLE COMPOSITE BRAKE SPECIFIC NO_x FOR VARIOUS AIR BOX BLEED RATES--LOW-SAC INJECTORS AT STANDARD TIMING

Concentrations for low-sac injectors and the 20 to 35 percent bleed rates are given in Table C-8 and shown in Figures C-42, C-43, and C-44 of Appendix C. The only substantial reduction in HC concentrations occurred in notches 7 and 8 (755 and 835 rpm) with 35 percent air bleed. In fact, there was an increase in HC over the baseline concentration at most points of the test cycle. Concentrations of CO were greatly increased by use of air box bleed, especially at the higher notch positions. The 35 percent bleed rate reduced NO_x by over 30 percent in notches 5 to 8. Little or no improvement was noted at idle and in the first two notches with either bleed rate.

The modal smoke opacity for these tests is summarized in Table 15 and shown in Figures 28 and 29. With needle injectors the smoke became excessive (i.e., greater than about six or seven percent opacity) in notch positions 5 to 8 with 50 percent air bleed, in notches 6 to 8 for 35 percent bleed, and in notch 8 only with 20 percent air bleed. The range of these "excessive" opacities was from 10 to 37 percent. The low-sac injectors, although generally characterized by lower smoke opacity than the needle units, also produced excessive smoke at certain test points. In particular, smoke opacity in notches 6 to 8 for 35 percent air bleed and notch 8 for 20 percent bleed, was above the specified limit. These opacities ranged from about 9 to 23 percent.

In view of these excessive opacities, it was decided to attempt to limit the smoke opacity by engine power derating. During tests with low-sac injectors, a number of extra modes were performed with engine power cut back by the amount necessary to reduce smoke to the desired opacity range. The computer calculations were then done using the data from both the so-called "normal" modes and from the "derated" modes. Only G. E. weight factors were used when calculating the "derated" quantities, since the ATSF schedule attaches little or no weight to the higher notch positions. The computer printouts for these tests are also included in Appendix B as Tables B-131 through B-132. The pertinent information is summarized in Table 16 of the text.

Cycle composite emissions of HC and NO_x were increased slightly by derating, while CO was decreased greatly. This behavior is, of course, reflected in the modal brake specific emissions. The modal fuel specific emissions exhibit these same trends. Smoke opacity was reduced to four- to six-percent. Power in notch 8 was reduced 12 percent with 20 percent air bleed and 29 percent with 35 percent air bleed. Power in notch positions 6 and 7 was reduced by 12 and 14 percent, respectively, with 35 percent bleed. The large amount of derating required in notch 8, with 35 percent air bleed, suggests

TABLE 15. MODAL SMOKE OPACITY FOR NEEDLE-VALVE AND LOW-SAC INJECTORS, STANDARD TIMING, AND AIR BOX BLEED

Mode	Notch Position	Engine Speed, rpm	PHS Smoke Opacity, %				
			0% Air Bleed*	10%*	20%*	35%*	50%*
	Needle Injectors						
1, 6, 11	Low Idle	285	0.8	1.0	1.2	1.7	1.5
2	1	285	1.4	1.6	2.0	2.5	3.8
3	2	344	1.5	1.2	1.5	1.8	2.8
4	3	424	1.9	1.2	1.5	2.8	4.0
5	4	515	1.7	1.5	2.2	3.5	7.2
7	5	584	1.4	1.5	2.5	5.5	14.0
8	6	675	1.8	2.2	3.5	7.0	19.5
9	7	755	2.6	3.9	4.5	10.8	25.0
10	8	835	4.6	6.5	9.8	20.5	37.0
	Low-Sac Injectors						
1, 6, 11	Low Idle	283	1.0	-	1.0	1.0	-
2	1	285	1.2	-	2.0	1.5	-
3	2	344	1.2	-	2.0	1.8	-
4	3	424	1.3	-	1.8	3.0	-
5	4	515	2.3	-	2.8	5.0	-
7	5	584	1.8	-	3.8	6.5	-
8	6	675	2.3	-	3.5	8.8	-
9	7	755	2.5	-	4.5	13.2	-
10	8	835	3.8	-	11.5	23.0	-

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*Percent of engine air flow mass requirement per mode.

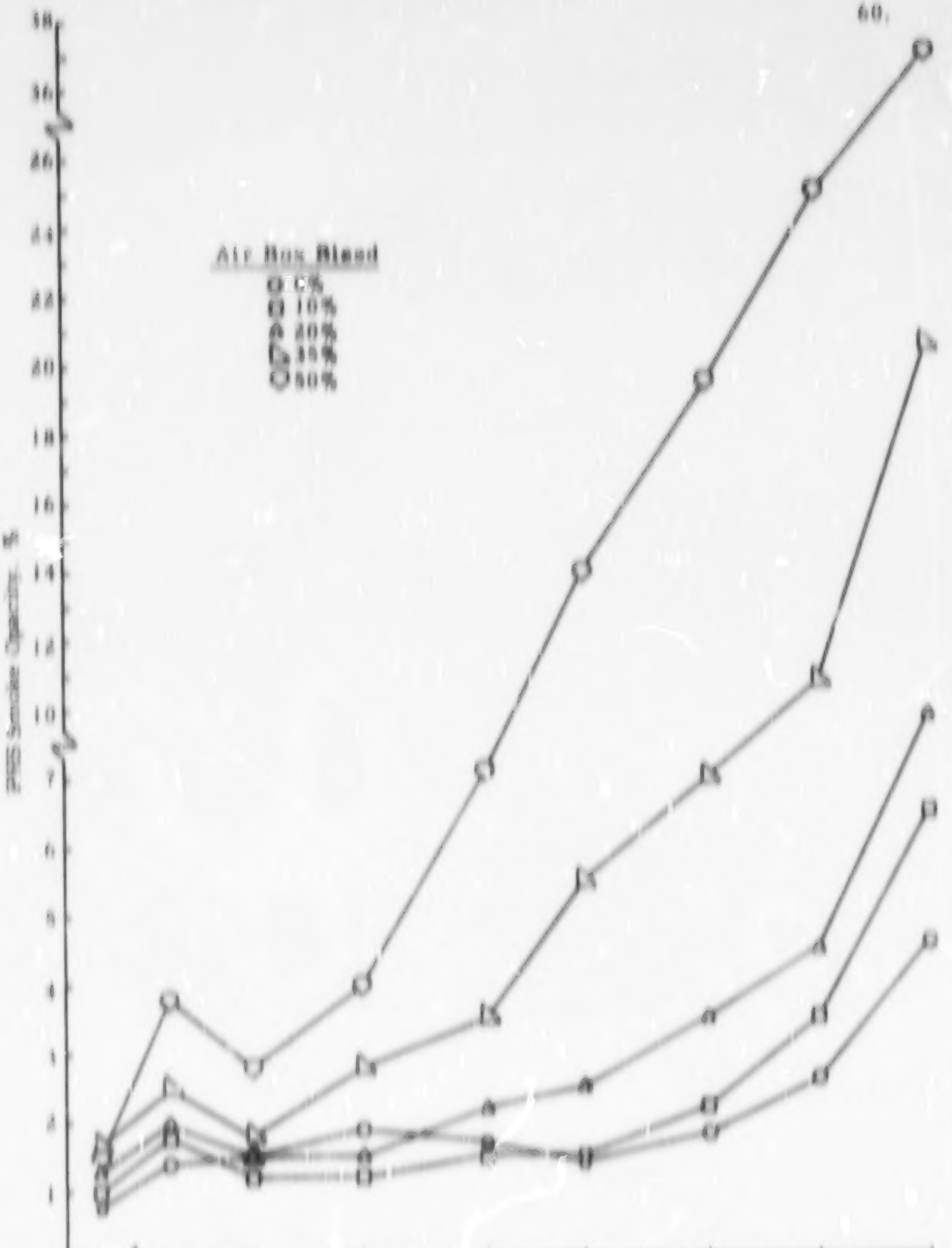

FIGURE 28. MODAL SMOKE OPACITY LEVELS FOR VARIOUS AIR BOX BLEED RATES--NEEDLE-VALVE INJECTORS AT STANDARD TIMING

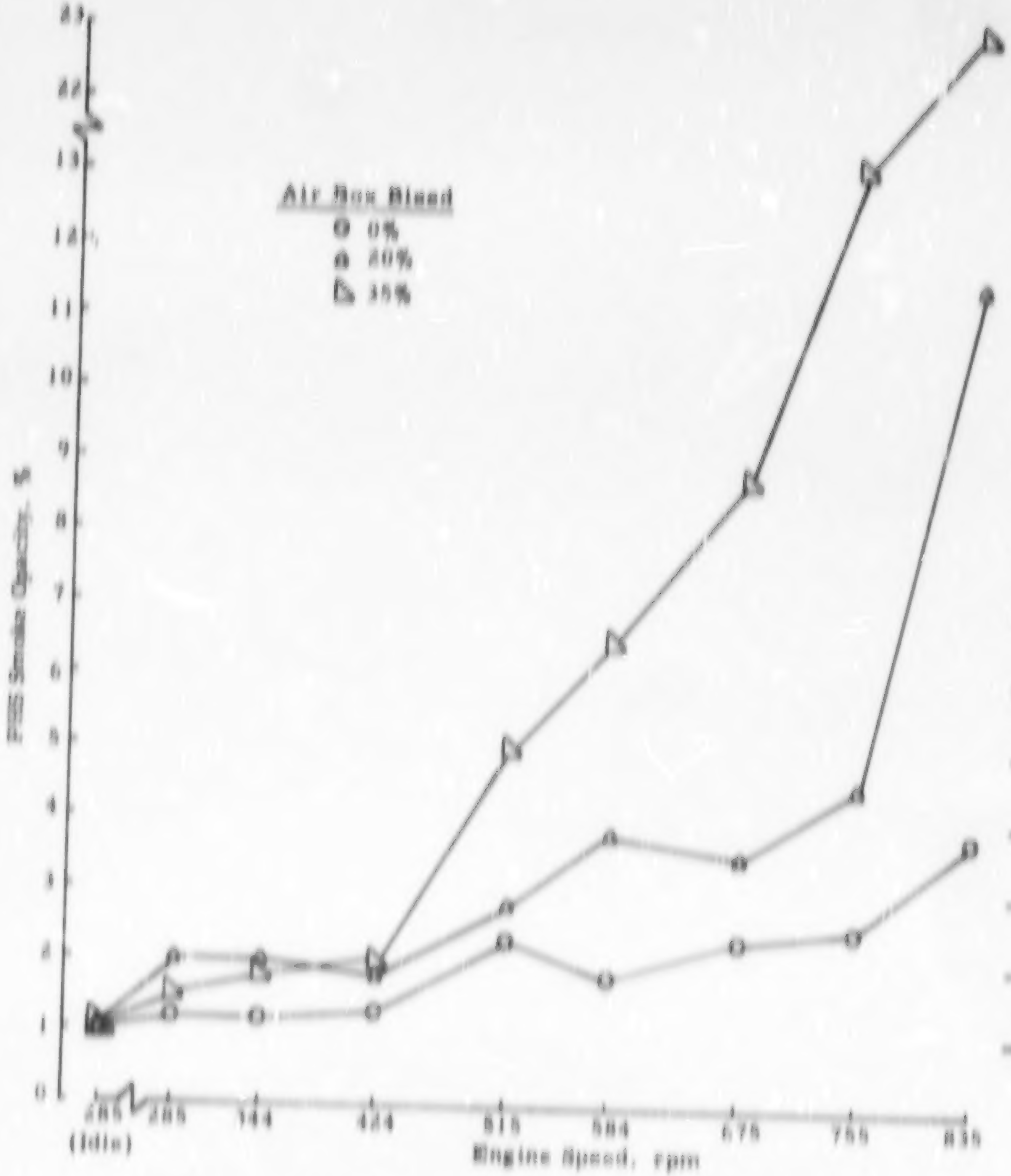

FIGURE 29. MODAL SMOKE OPACITY LEVELS FOR VARIOUS AIR BOX BLEED RATES--LOW-SAC INJECTORS AT STANDARD TIMING

TABLE 16. EFFECT OF DERATING ON EMISSIONS, SMOKE, AND POWER--LOW-SAC INJECTORS, STANDARD TIMING, AND AIR BOX BLEED

Air Box Bleed, %*	Cycle Composite Emissions BSHC Normal	BSHC Derate	BSCO Normal	BSCO Derate	$BSNO_x$ Normal	$BSNO_x$ Derate
20	0.611	0.706	16.612	5.718	9.522	11.148
35	0.339	0.520	17.252	7.761	7.151	8.456

Air Box Bleed, %*	Notch Position	Modal Emissions, Smoke, and Power BSHC Normal	BSHC Derate	BSCO Normal	BSCO Derate	$BSNO_x$ Normal	$BSNO_x$ Derate
20	8	0.51	0.62	20.19	5.89	8.76	10.86
35	6	0.34	0.38	11.29	4.54	6.47	6.82
	7	0.26	0.39	18.19	4.82	6.74	7.26
	8	0.25	0.46	19.66	9.16	6.66	8.21

Air Box Bleed, %*	Notch Position	FSHC Normal	FSHC Derate	FSCO Normal	FSCO Derate	$FSNO_x$ Normal	$FSNO_x$ Derate
20	8	1.05	1.34	41.72	12.58	18.10	23.20
35	6	0.74	0.84	24.41	9.99	13.98	15.04
	7	0.53	0.84	37.47	10.39	13.90	15.63
	8	0.48	0.92	37.57	18.58	12.74	16.58

Air Box Bleed, %*	Notch Position	Smoke, % Normal	Smoke, % Derate	Power, Bhp Normal	Power, Bhp Derate
20	8	11.5	4.0	194	170
35	6	8.8	5.8	130	115
	7	13.2	6.0	156	134
	8	23.0	5.5	180	127

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*Percent of engine air flow mass requirement per mode.

that the higher bleed rates may not be suitable in the high-power notch positions. Also, it should be noted that in all likelihood even more derating would be necessary with the needle injectors, since these produce more smoke than the low-sac models.

The modal brake specific and fuel specific emissions for the "normal" (non-derated) tests with needle and low-sac injectors are given in Tables C-9 and C-10, respectively, and illustrated by Figures C-46 through C-50 (needle) and C-51 through C-55 (low-sac). These data illustrate two salient points concerning air box bleed and gaseous emissions; namely, that CO is greatly increased and NO_x is substantially reduced. However, in this instance, the reduction in NO_x was caused principally by the reduced exhaust mass, due to the air bleed itself.

One additional point to be mentioned concerns the effect of air box bleed on engine operation. Considerable engine roughness was present at 50 percent air bleed and a lesser, but still obvious, amount for 35 percent bleed. This roughness occurred in the form of fluctuations in speed, load, and fuel rate, all of which are usually very stable. This problem was not present at the 10 and 20 percent bleed rates. Engine power output was also adversely affected by the higher bleed rates. Observed power losses of 15 to 20 percent were not unusual at 35 and 50 percent air bleed.

F. Effect of Cooled EGR on Emissions--Needle-Valve and Low-Sac Injectors at Standard Timing

Exhaust gas cooled to 125-150° F was recirculated into the engine intake system. The amount recirculated was equal to a nominal 10, 20, or 30 percent of the air flow mass requirement of the engine. The nominal 10 percent rate was omitted for tests conducted with low-sac injectors. The computer printouts for all tests are contained in Appendix B, Tables B-153 through B-162.

The average cycle composite emissions are given in Table 17 and illustrated in Figures 30 and 31 (needle injectors) and 32 and 33 (low-sac). Since the exhaust mass from the engine is reduced by the amount recirculated, the mass flow (g/hr) of HC, CO, and NO_x is influenced by this reduced exhaust mass, as well as by any increase or decrease in the concentrations of these contaminants. Brake specific emissions are also affected by the change in engine horsepower produced by EGR.

When used with needle injectors, cooled EGR resulted in reduced BSHC for the ATSF switch cycle, but showed little or no improvement for

TABLE 17. CYCLE COMPOSITE BRAKE SPECIFIC EMISSIONS FOR NEEDLE-VALVE AND LOW-SAC INJECTORS, STANDARD TIMING, AND COOLED EGR

Injectors	Nominal EGR %*	BSHC	BSCO	BSNO$_x$	BSHC + BSNO$_x$
		ATSF Weight Factor Schedule			
Needle	0	4.553	4.139	19.562	24.115
	10	2.580	3.323	14.655	17.235
	20	2.318	2.746	12.071	14.390
	30	2.265	3.616	10.784	13.049
Low-Sac	0	1.837	2.702	22.563	24.400
	10	-	-	-	-
	20	1.108	2.852	15.642	16.750
	30	1.438	3.351	13.710	15.148
		G.E. Weight Factor Schedule			
Needle	0	1.106	10.568	9.823	10.929
	10	0.942	12.164	7.448	8.390
	20	0.959	17.682	4.764	5.722
	30	0.893	21.284	3.574	4.468
Low-Sac	0	0.655	7.281	13.045	13.700
	10	-	-	-	-
	20	0.510	17.949	6.422	6.932
	30	0.532	19.504	4.922	5.456

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*Percent of engine air flow mass requirement per mode.

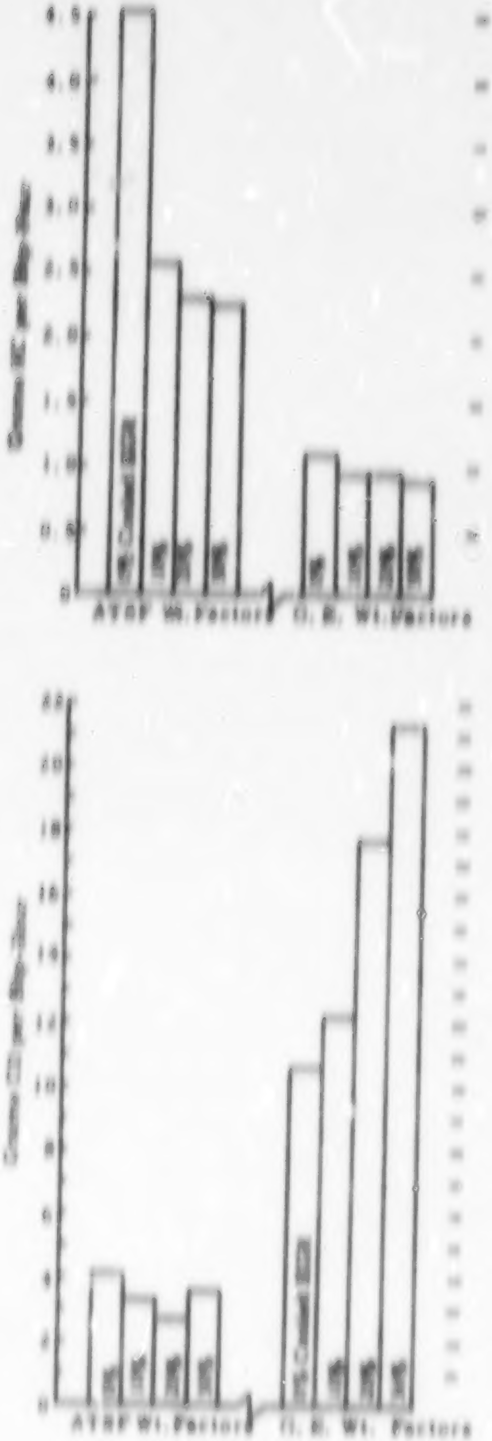

FIGURE 18. CYCLE COMPOSITE BRAKE SPECIFIC HC AND CO FOR VARIOUS RATES OF COOLED EGR - NEEDLE-VALVE INJECTORS AT STANDARD TIMING

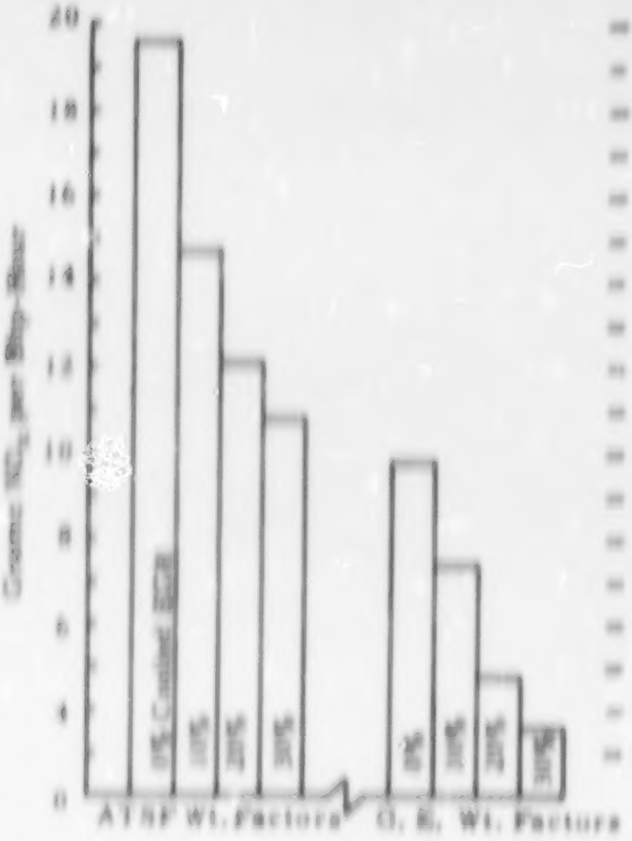

FIGURE 31. CYCLE COMPOSITE BRAKE SPECIFIC NO$_x$ FOR VARIOUS RATES OF COOLED EGR--NEEDLE-VALVE INJECTORS AT STANDARD TIMING

the G. E. line haul cycle. Brake specific CO was doubled by 30 percent EGR for the line haul cycle, where emphasis is on the higher notch positions. Cycle composite NO$_x$ showed worthwhile reductions with all three EGR rates and both weighting schedules. These reductions ranged from 25 to 45 percent for the switch cycle, to 24 to 63 percent for the line haul.

When used in conjunction with low-sac injectors, cooled EGR reduced BSHC at the 20 percent rate, but increased it at the 30 percent rate. Brake specific CO was almost tripled on the G. E. cycle by 30 percent EGR. Cycle composite NO$_x$ was reduced considerably in all cases. The reductions ranged from 31 to 39 percent for the ATSF cycle, and from 51 to 62 percent for the G. E. cycle. These reductions are commensurate to those observed with needle injectors and the 20 and 30 percent EGR rates.

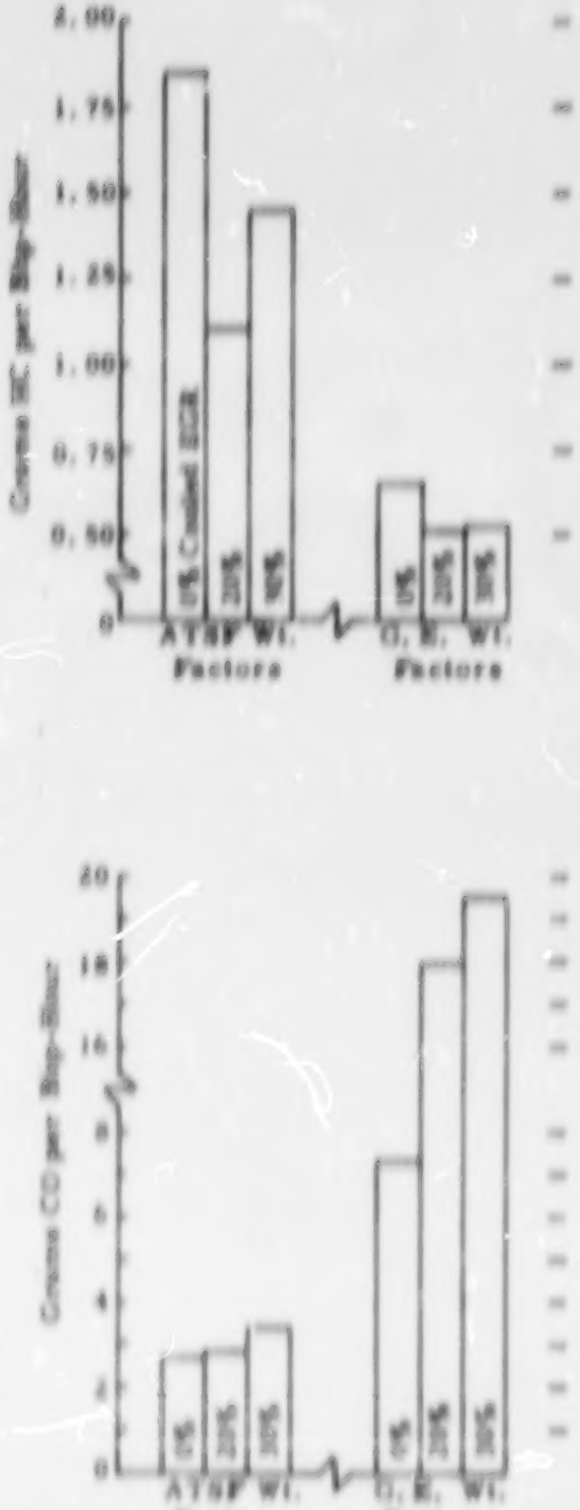

FIGURE 12. CYCLE COMPOSITE BRAKE SPECIFIC HC AND CO FOR VARIOUS RATES OF COOLED EGR--LOW-SAC INJECTORS AT STANDARD TIMING

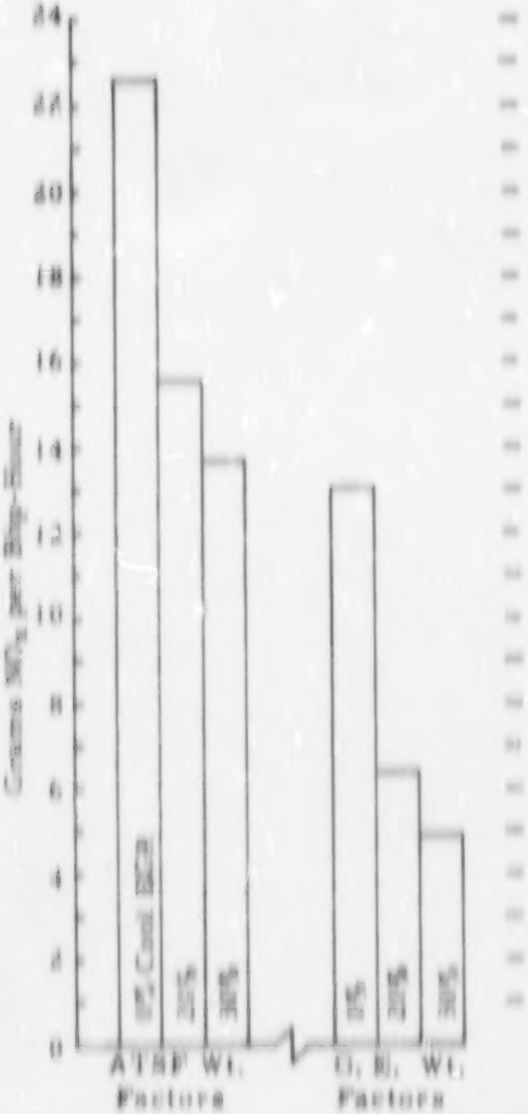

FIGURE 11. CYCLE COMPOSITE BRAKE SPECIFIC NO_x FOR VARIOUS RATES OF COOLED EGR--LOW-SAC INJECTORS AT STANDARD TIMING

Table C-11 and Figures C-56 through C-58 of Appendix C are concerned with the modal emissions concentrations for the needle injectors. Similar data for the low-sac injectors is given in Table C-12 and Figures C-59 through C-61. The principal effects of cooled EGR were a drastic increase in CO concentrations, usually beginning in notch position 4 or 5, and a substantial decrease in NO_x concentrations beginning in notches 4 to 8 (515 to 835 rpm). With needle injectors, the 20 percent EGR rate reduced NO_x by 21 to 48 percent of baseline (0 percent EGR) values in these notches, while the nominal 30 percent EGR rate produced reductions of 37 to 58 percent. With low-sac injectors, the corresponding reductions were 22 to 48 percent with 20 percent EGR and 36 to 56 percent with 30 percent EGR.

Smoke opacity data are given in Table 18 and illustrated in Figures 34 and 35. Cooled EGR, in conjunction with needle injectors, produced smoke above the established limit (about six-percent opacity) in notch 7 (30 percent EGR) and notch 8 (all three rates of EGR). The range of these "excessive" opacities was about 9 to 24 percent (Figure 34). Low-sac injectors and cooled EGR produced excessive smoke in these same notch positions, and the opacity range was 9 to 15 percent (Figure 35).

The Project Officer requested that the relation between excessive smoke opacity and the oxygen-fuel ratio be determined for the tests with EGR. In other words, the O_2-fuel ratio at which smoke opacity exceeded the nominal baseline limit should be determined. Toward this end, the excess O_2 content of the exhaust was measured during a series of baseline-type tests (i.e., no EGR, air bleed, and so forth). The mass flow of excess O_2 was calculated in lb/min at standard temperature and pressure, and divided by the observed fuel flow mass to obtain a ratio of excess O_2 to fuel. The excess O_2 in the exhaust was measured during tests with cooled EGR, and the resulting O_2-fuel ratio computed according to the procedure outlined above. The results are presented in the computer printouts in the columns labeled "O_2 Pct" (lower half of table) and "O_2-Fuel Ratio" (upper half of table).

Table 19 summarizes the excess O_2 concentrations and calculated O_2-fuel ratios for tests with both types of injectors. The O_2 fuel ratios are illustrated in Figures 36 (needle) and 37 (low-sac). It can be seen from the smoke opacity data for the needle injectors (Table 18 and Figure 34) that smoke exceeded the nominal baseline limit by a substantial amount at three points--notches 7 and 8 for 30 percent EGR, notch 8 only for 20 percent and notch 7 for 20 percent. The dashed line across Figure 36 closely approximates the point (about 4.0) below which smoke opacity becomes, by definition, excessive.

A similar analysis can be performed using the opacity data for the low-sac injectors (Table 18 and Figure 35). In this case, smoke exceeded the baseline limit by a substantial amount in notches 7 and 8 for 30 percent

TABLE 18. MODAL SMOKE OPACITY FOR NEEDLE-VALVE AND LOW-SAC INJECTORS, STANDARD TIMING, AND COOLED EGR

Mode	Notch Position	Engine Speed, rpm	PHS Smoke Opacity, %			
			0% EGR*	10%*	20%*	30%*
	Needle Injectors					
1, 6, 11	Low Idle	285	0.8	1.1	1.1	1.2
2	1	285	1.4	1.5	1.2	1.7
3	2	344	1.5	1.2	1.1	1.8
4	3	424	1.9	1.8	1.0	2.0
5	4	515	1.7	2.5	1.8	2.5
7	5	584	1.4	1.2	2.0	4.3
8	6	675	1.6	3.5	3.5	6.5
9	7	755	2.6	4.5	6.8	11.2
10	8	835	4.6	9.2	17.2	24.5
	Low-Sac Injectors					
1, 6, 11	Low Idle	285	1.0	c	1.6	1.0
2	1	285	1.2	c	1.0	1.5
3	2	344	1.2	c	1.2	1.8
4	3	424	1.3	c	1.2	2.0
5	4	515	2.3	c	3.0	2.8
7	5	575	1.8	c	2.5	2.5
8	6	675	2.3	c	3.0	4.2
9	7	755	2.5	c	5.2	5.0
10	8	835	3.8	c	11.5	15.3

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*Percent of engine air flow mass requirement per mode.

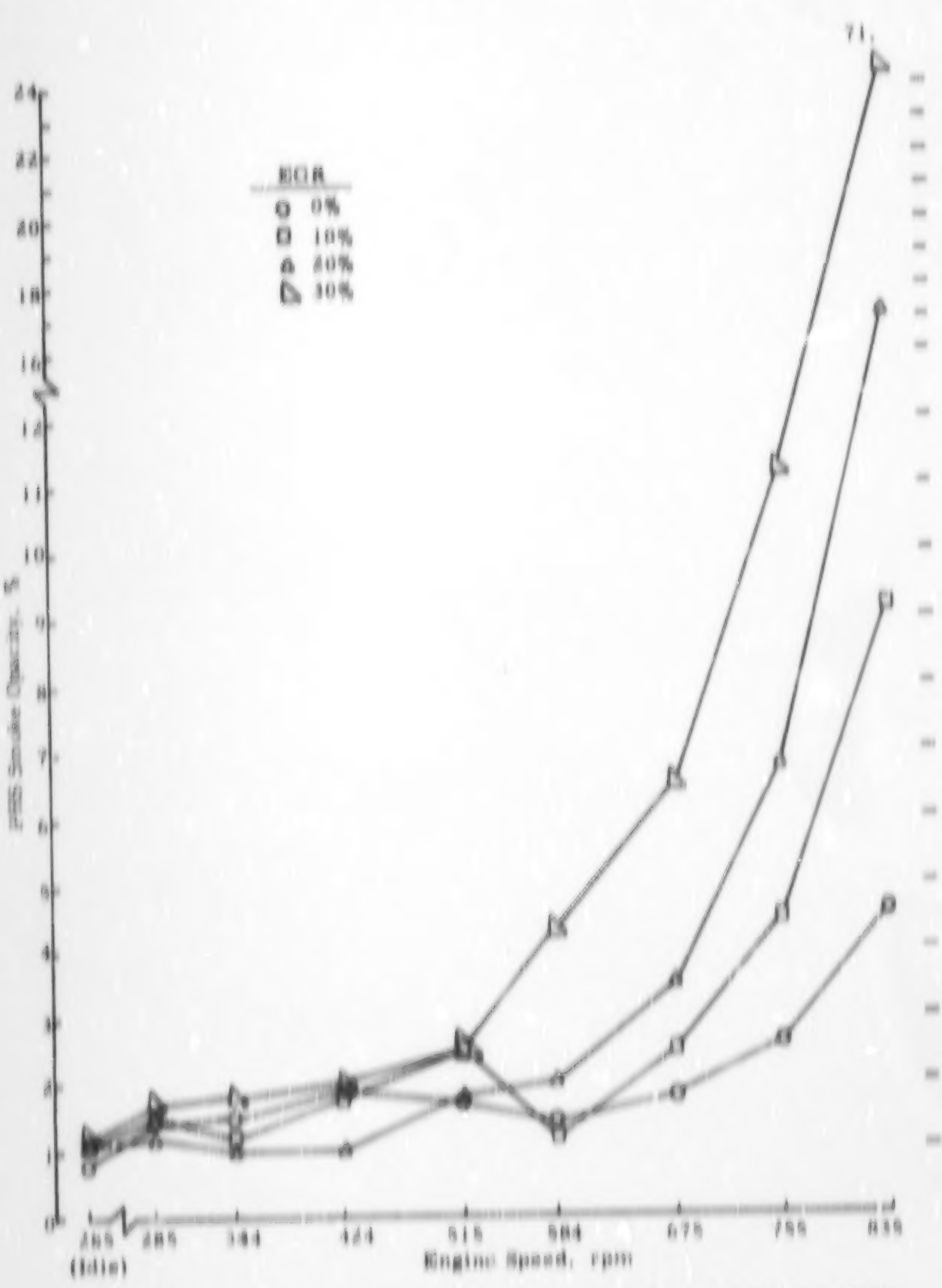

FIGURE 34. MODAL SMOKE OPACITY LEVELS FOR VARIOUS RATES OF COOLED EGR--NEEDLE-VALVE INJECTORS AT STANDARD TIMING

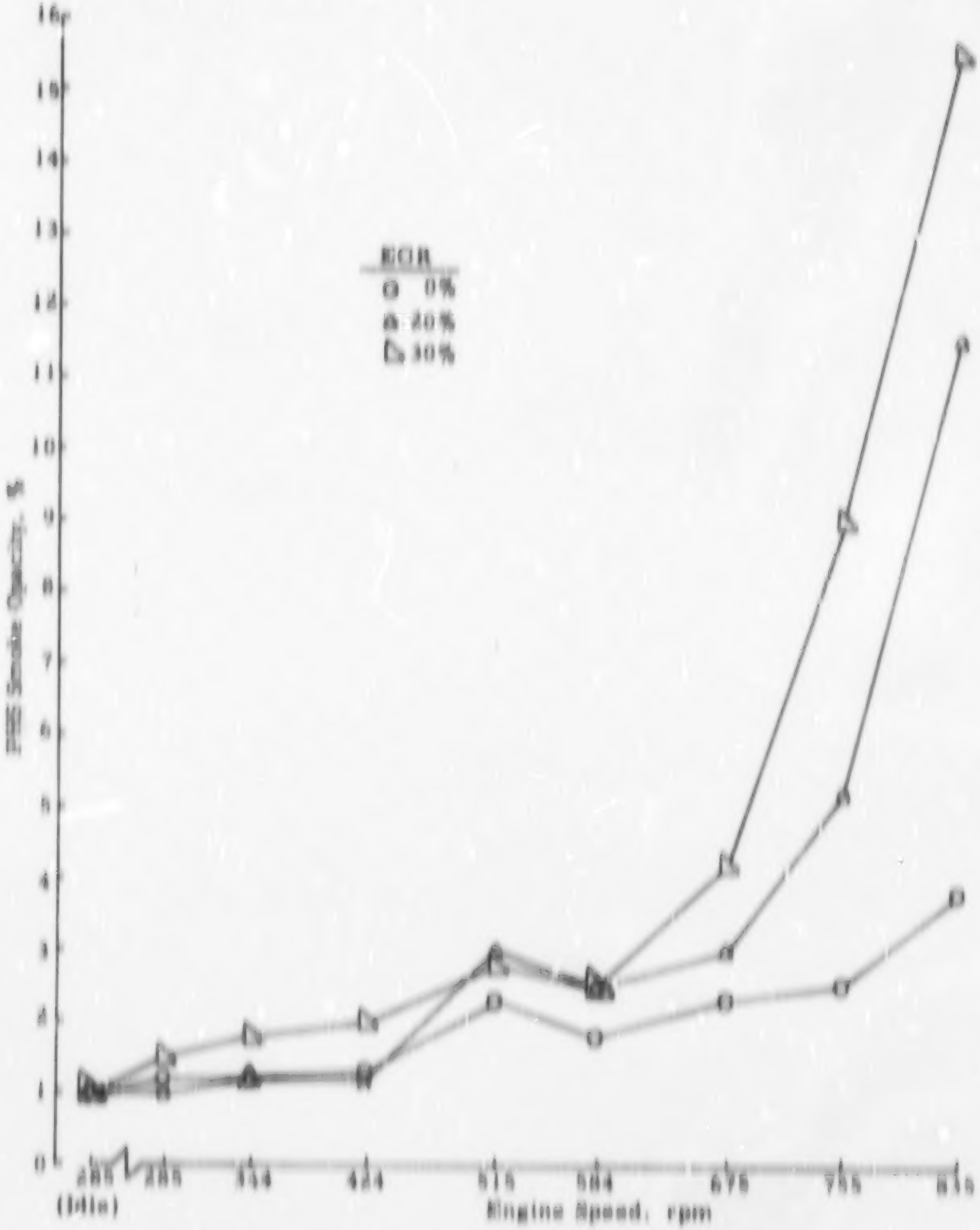

FIGURE 15. MODAL SMOKE OPACITY LEVELS FOR VARIOUS RATES OF COOLED EGR--LOW-SAC INJECTORS AT STANDARD TIMING

TABLE 19. EXCESS O_2 CONCENTRATIONS AND O_2-FUEL RATIOS FOR COOLED EGR--NEEDLE-VALVE AND LOW-SAC INJECTORS AT STANDARD TIMING

Notch	0% EGR		10% EGR		20% EGR		30% EGR	
Position	O_2, %	O_2/Fuel	O_2, %	O_2/Fuel	O_2, %	O_2/Fuel	O_2, %	O_2/Fuel
			Needle-Valve Injectors					
Low Idle	20.1	58.85	20.0	57.78	20.2	49.19	20.1	45.26
1	19.0	24.54	19.4	23.63	19.0	19.85	18.8	18.69
2	18.3	17.76	18.5	16.83	18.4	14.72	18.0	13.08
3	17.1	11.59	17.4	10.90	16.9	9.15	16.2	8.18
4	16.2	9.20	16.5	8.79	16.1	7.69	15.2	6.00
5	15.2	7.42	15.8	7.06	14.9	6.04	13.9	4.76
6	14.4	6.09	15.0	5.95	13.9	4.93	12.9	4.04
7	13.8	5.28	14.4	5.11	13.2	4.18	12.4	3.64
8	12.8	4.37	13.6	4.28	12.2	3.51	11.5	2.92
			Low-Sac Injectors					
Low Idle	20.2	57.56	◦	◦	20.4	55.75	19.9	49.64
1	19.4	25.23	◦	◦	20.0	23.42	18.4	19.50
2	18.8	18.85	◦	◦	18.8	16.57	17.2	13.51
3	17.7	12.78	◦	◦	17.4	10.66	15.4	8.38
4	17.1	10.46	◦	◦	16.4	8.36	14.4	6.60
5	15.9	8.14	◦	◦	15.0	6.54	13.4	5.20
6	15.2	6.93	◦	◦	14.3	5.43	12.6	4.38
7	14.6	6.07	◦	◦	13.8	4.82	12.0	3.77
8	13.8	5.09	◦	◦	13.4	4.14	11.6	3.23

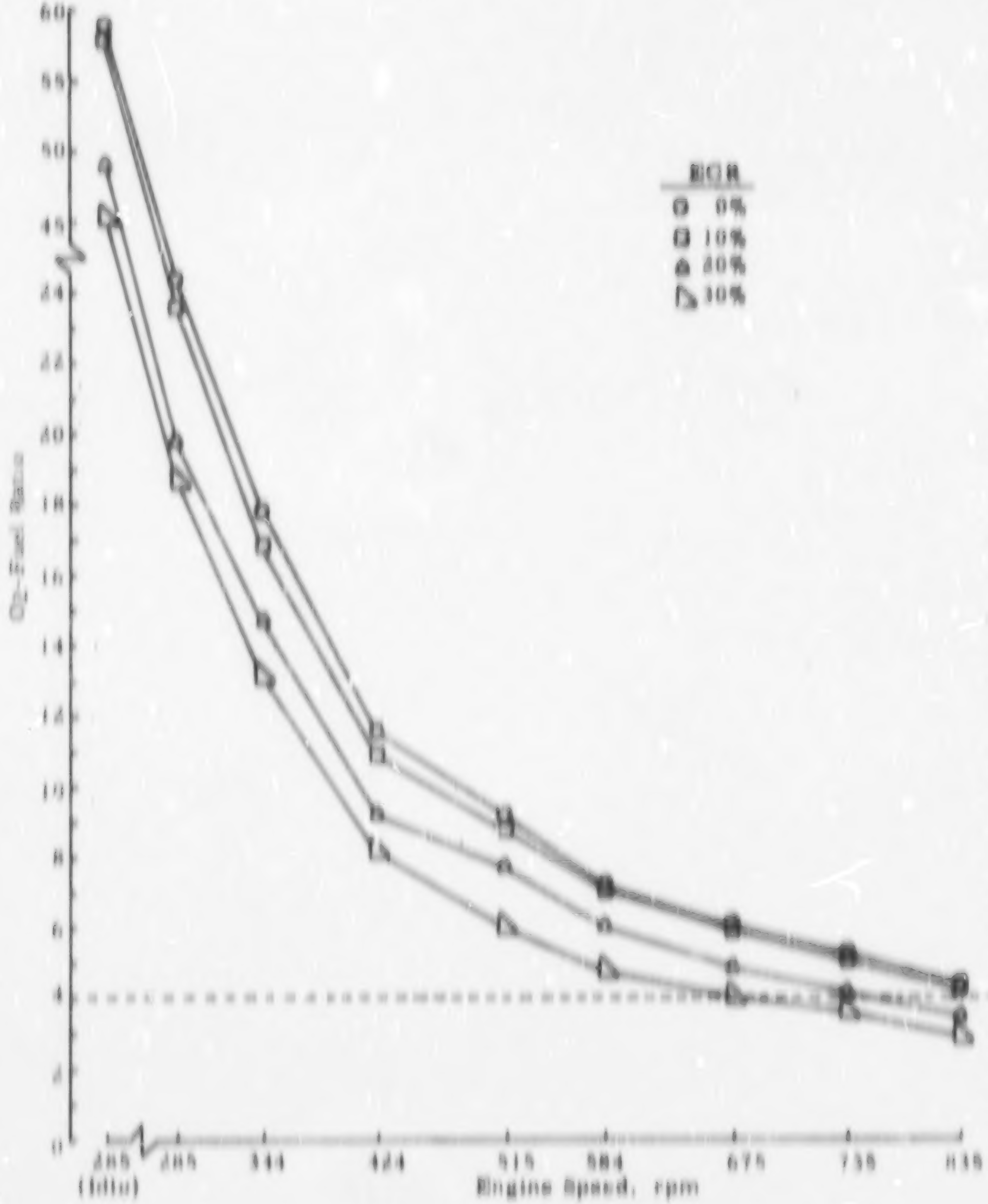

FIGURE 36. MODAL O_2-FUEL RATIOS FOR VARIOUS RATES OF COOLED EGR - NEEDLE-VALVE INJECTORS AT STANDARD TIMING

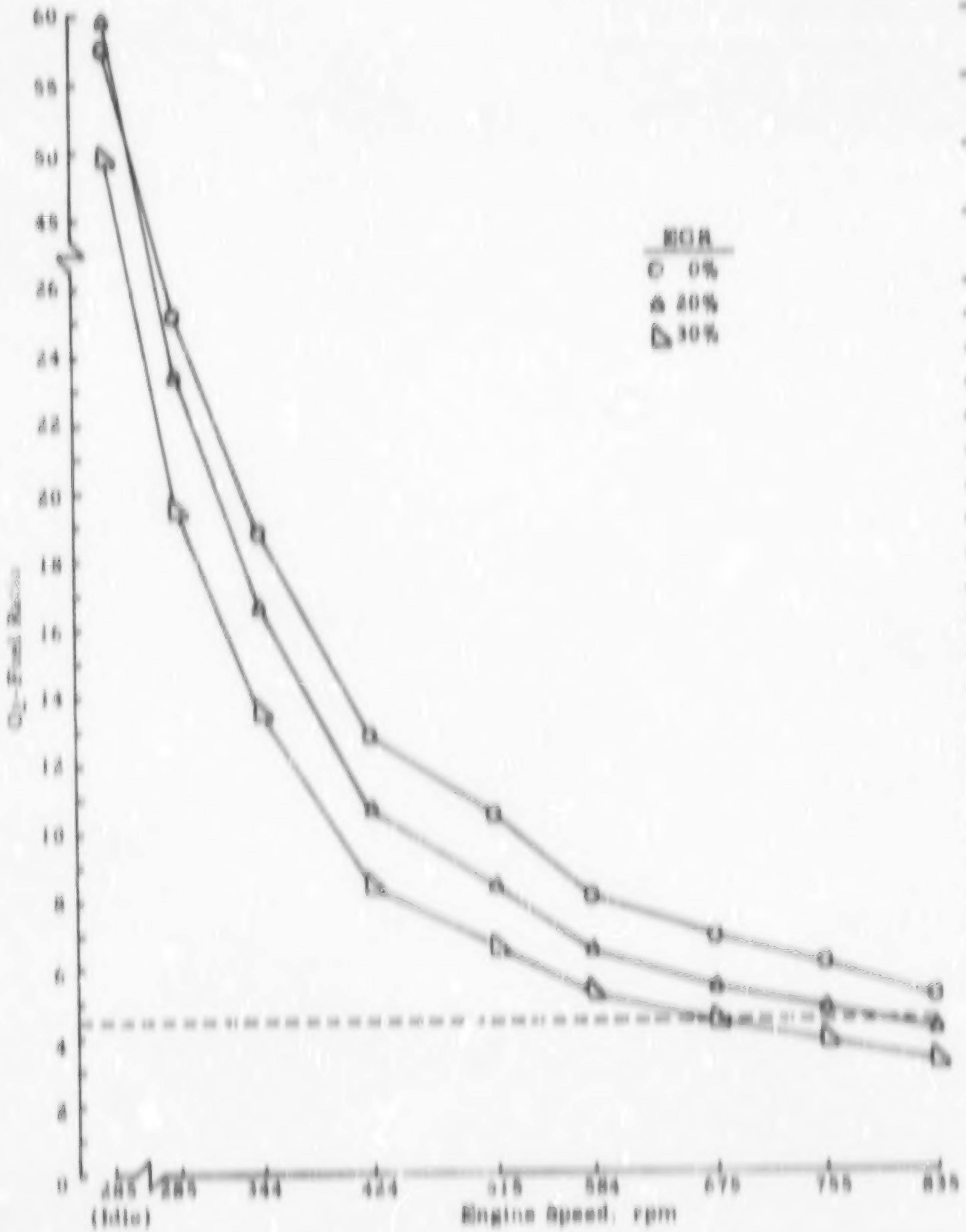

FIGURE 17. MODAL O_2-FUEL RATIOS FOR VARIOUS RATES OF COOLED EGR--LOW-SAC INJECTORS AT STANDARD TIMING

EGR and notch 8 only for 20 percent EGR. The dashed line in Figure 37 approximates the point (about 4.4) where smoke became "excessive".

Engine power was derated in these notch positions in order to determine the amount of derating needed to reduce smoke levels to nominal baseline values. The so-called "normal" and "derated" test results are summarized in Tables 20 and 21 for needle and low-sac injectors, respectively. The pertinent computer printouts are Tables B-155 through B-162 in Appendix B.

With either type of injector, derating generally resulted in increased HC and NO_x and decreased CO, on both a brake specific and fuel specific basis. The ratio of excess O_2 to fuel was, of course, increased, and the ratios produced by derating fell between 4.0 and 5.0 for low-sac injectors and between 4.8 and 5.6 for needle injectors. These ratios are slightly higher than those from the baseline tests; however, the amount of derating was in excess of what was needed to reduce smoke to baseline values, and this extra derating caused the O_2-fuel ratios to increase. Power was reduced in these notch positions by 19 to 41 percent with needle injectors and by a more reasonable 11 to 14 percent with the low-sac units.

Without derating, engine power was affected only slightly by cooled EGR. Even at the nominal 30 percent rate, power was reduced by only five percent. This is a great improvement over the sizable power reductions found to occur with the higher rates of air box bleed.

Modal brake specific and fuel specific emissions for tests without derating are presented in Table C-13 and Figures C-62 through C-67 for needle injectors and in Table C-14 and Figures C-68 to C-73 for low-sacs. These data show that cooled EGR reduced HC in all notch positions, increased CO greatly in the higher notches, and reduced NO_x at all points, especially in the higher notches. In general, the higher the EGR rate, the greater was the reduction in NO_x.

G. Effect of Hot EGR on Emissions - Needle-Valve and Low-Sac Injectors at Standard Timing

These tests were conducted without cooling the recirculated exhaust gas, and the minimum temperature of the EGR was 200° F. In all other respects these tests were identical to those done with cooled EGR. The amount of recirculated exhaust was equal to a nominal 10, 20, or 30 percent of the engine intake air mass required per mode. Only the 20 and 30 percent rates were used with low-sac injectors.

The computer printouts for these tests are Tables B-163 through B-178 of Appendix B. Cycle composite emissions are summarized in Table 22 and shown in Figures 38 through 41. Brake specific HC for the ATSF cycle was significantly lower in most tests; however, little or no

TABLE 20. EFFECT OF DERATING ON EMISSIONS, SMOKE, AND POWER--NEEDLE-VALVE INJECTORS, STANDARD TIMING, AND COOLED EGR

EGR Rate, %*	Cycle Composite Emissions					
	BSHC		BSCO		BSNO$_x$	
	Normal	Derate	Normal	Derate	Normal	Derate
20	0.959	1.008	17.682	3.824	4.764	6.366
30	0.893	1.064	41.284	2.342	3.574	5.420

EGR Rate, %	Notch Position	Modal Emissions, Smoke and Power					
		BSHC		BSCO		BSNO$_x$	
		Normal	Derate	Normal	Derate	Normal	Derate
20	8	0.91	0.96	21.87	3.67	4.06	6.09
30	7	0.76	0.78	12.64	2.52	3.37	4.66
	8	0.87	1.06	26.08	2.00	2.96	5.12
		FSHC		FSCO		FSNO$_x$	
		Normal	Derate	Normal	Derate	Normal	Derate
20	8	1.91	1.96	46.14	7.52	8.56	12.46
30	7	1.65	1.68	27.40	5.42	7.30	10.02
	8	1.69	1.98	53.14	3.77	6.05	9.60
		Excess O$_2$, %		Smoke, %		Power, Bhp	
		Normal	Derate	Normal	Derate	Normal	Derate
20	8	3.51	5.10	17.2	5.2	198	148
30	7	3.64	4.84	11.2	4.8	165	133
	8	2.92	5.62	24.5	0.0	192	114

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*Percent of engine air flow mass requirement per mode.

TABLE 21. EFFECT OF DERATING ON EMISSIONS, SMOKE, AND POWER--LOW-SAC INJECTORS, STANDARD TIMING, AND COOLED EGR

EGR Rate, %[a]	Cycle Composite Emissions					
	BSHC		BSCO		BSNO$_x$	
	Normal	Derate	Normal	Derate	Normal	Derate
20	0.510	0.537	17.949	7.096	6.422	7.452
30	0.532	0.603	19.504	7.262	4.922	6.056

EGR Rate, %[a]	Notch Position	Modal Emissions, Smoke, and Power					
		BSHC		BSCO		BSNO$_x$	
		Normal	Derate	Normal	Derate	Normal	Derate
20	8	0.49	0.52	22.23	8.12	5.40	6.66
30	7	0.50	0.48	13.70	4.04	4.64	5.60
	6	0.49	0.57	23.76	2.76	4.13	5.43
		FSHC		FSCO		FSNO$_x$	
		Normal	Derate	Normal	Derate	Normal	Derate
20	8	1.09	1.18	48.89	18.16	11.87	14.90
30	7	1.13	1.10	31.42	9.24	10.64	12.80
	6	1.04	1.24	51.54	19.11	8.95	11.86
		O$_2$-Fuel Ratio		Smoke, %		Power, Bhp	
		Normal	Derate	Normal	Derate	Normal	Derate
20	8	4.14	4.92	11.5	4.2	206	184
30	7	3.77	4.61	9.0	4.2	174	152
	6	3.24	4.06	15.5	5.2	203	174

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[a] Percent of engine air flow mass requirement per mode.

TABLE 22. CYCLE COMPOSITE BRAKE SPECIFIC EMISSIONS FOR NEEDLE-VALVE AND LOW-SAC INJECTORS, STANDARD TIMING, AND HOT EGR

Injectors	Nominal EGR %*	BSHC	BSCO	BSNO$_x$	BSHC + BSNO$_x$
		ATSF Weight Factor Schedule			
Needle	0	4.557	4.139	19.562	24.119
	10	2.416	3.932	16.720	19.136
	20	2.252	3.845	14.115	16.367
	30	2.203	4.070	11.814	14.017
Low-Sac	0	1.837	2.702	22.563	24.400
	10	-	-	-	-
	20	1.176	3.224	13.360	14.536
	30	1.496	3.372	13.762	15.258
		G. E. Weight Factor Schedule			
Needle	0	1.106	10.968	9.823	10.929
	10	0.859	18.030	7.753	8.612
	20	0.835	27.367	5.345	6.180
	30	0.938	58.926	3.185	4.122
Low-Sac	0	0.655	7.281	13.045	13.700
	10	-	-	-	-
	20	0.473	33.357	5.249	5.722
	30	0.600	64.156	4.128	4.728

*Percent of engine air flow requirement per mode.

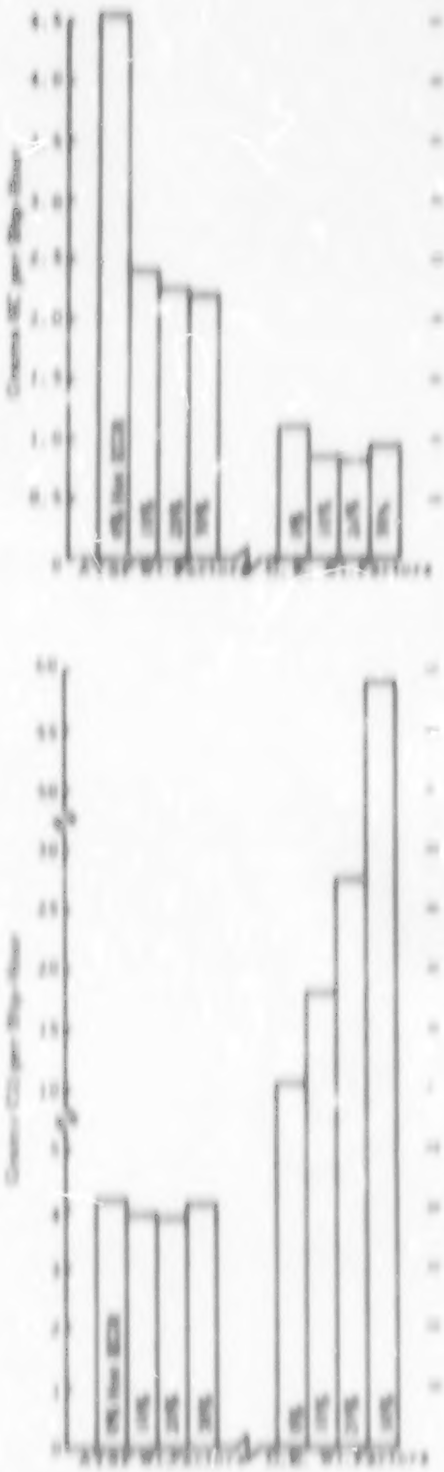

FIGURE 15. CYCLE COMPOSITE BRAKE SPECIFIC HC AND CO FOR VARIOUS RATES OF HOT EGR - NEEDLE VALVE INJECTORS AT STANDARD TIMING

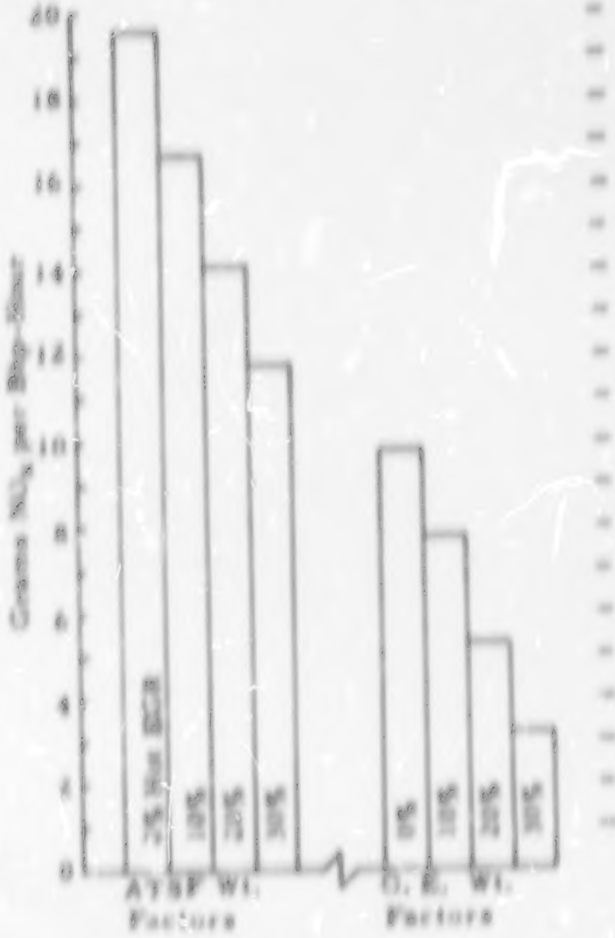

FIGURE 19. CYCLE COMPOSITE BRAKE SPECIFIC NO_x FOR VARIOUS RATES OF HOT EGR--NEEDLE-VALVE INJECTORS AT STANDARD TIMING

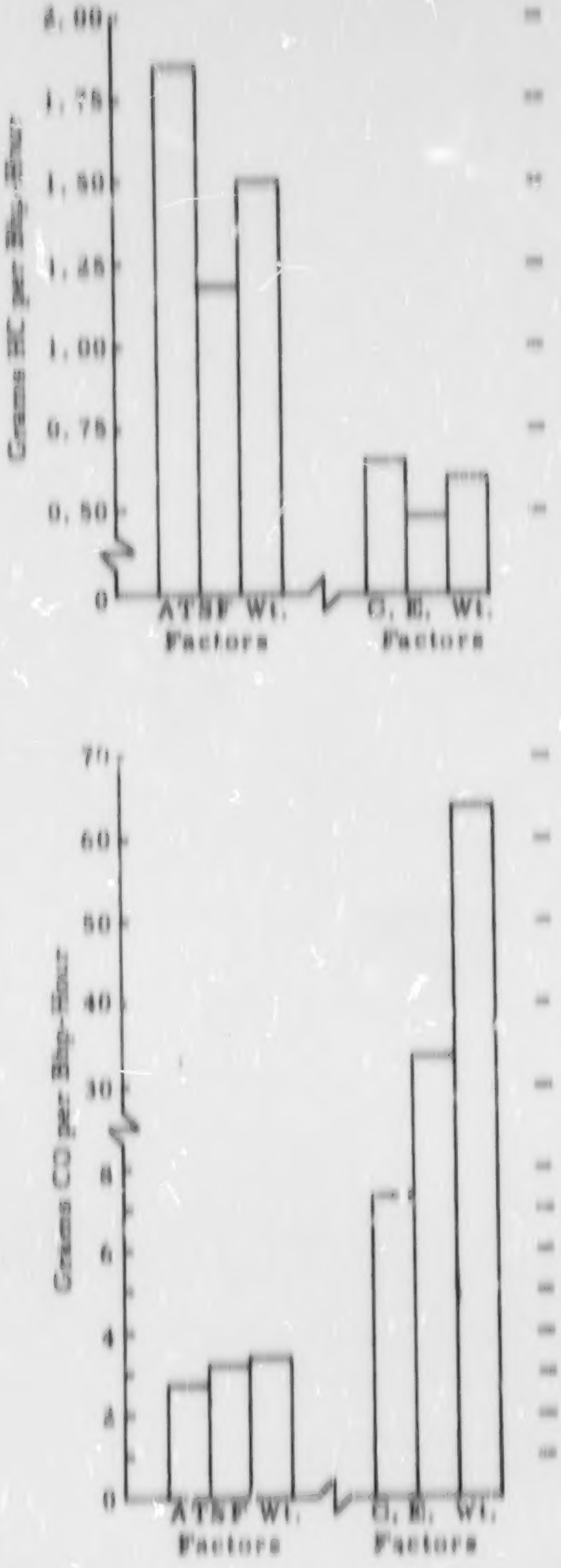

FIGURE 40. CYCLE COMPOSITE BRAKE SPECIFIC HC AND CO FOR VARIOUS RATES OF HOT EGR-- LOW-SAC INJECTORS AT STANDARD TIMING

improvement was present in HC calculated on the G. E. cycle. Brake specific CO was much higher with hot EGR, higher even than with cooled EGR or air box bleed. With nominal 30 percent EGR and using the line haul weight factors, BSCO was almost six times higher than baseline (0 percent EGR) for needle injectors and almost nine times higher for the low-sac units. Cycle composite NO_x was reduced by hot EGR in all tests, and the reductions were of the same magnitude (percentwise) as with cooled EGR. The ATSF cycle composite values were reduced 15 to 40 percent below baseline for needle injectors and by about 40 percent for low-sac injectors. The G. E. values were reduced 20 to 67 percent for needle injectors and by 60 to 68 percent for low-sacs. The lower percentage reduction for the needle injectors was achieved with the nominal 10 percent EGR rate, which was not used in tests with low-sac injectors.

Table C-15 and Figures C-73 through C-75 give the concentrations produced by needle injectors and hot EGR. Corresponding concentrations for the low-sac injectors are presented in Table C-16 and Figures C-76 through C-78. Hot EGR generally reduced the HC concentrations, especially in the lower notch positions, but this trend was not so evident with the low-sac injectors. Concentrations of CO were slightly increased or decreased at low idle and in the first four notches (285-515 rpm), while in the last four notches the concentrations were increased 1.5 to 7 times (depending on EGR rate) the baseline values for needle injectors and 3 to 12 times the baseline for low-sacs. These increases in CO were generally much higher than those noted with cooled EGR. Concentrations of NO_x were greatly reduced in notch positions 5 through 8 (584-835 rpm). With nominal 30 percent EGR, NO_x from the needle injectors was reduced by 33 to 74 percent in these notches, and by 42 to 73 percent with low-sac injectors.

Smoke opacity data for these tests appear in Table 23 and Figures 42 and 43. Hot EGR tended to increase smoke in most modes, but once again the largest increases were found in the higher notch positions. Opacity was above the baseline limit for needle injectors at six points--notches 6, 7, and 8 for 30 percent EGR notches 7 and 8 for 20 percent, and notch 8 only for 10 percent EGR. The range of these opacities was 7 to 59 percent. The combination of low-sac injectors and hot EGR resulted in excessive smoke in notch positions 6, 7, and 8 for the 30 percent rate, and in notches 7 and 8 for 20 percent EGR. The opacity range in this case was 7 to 54 percent.

The amount of excess O_2 in the exhaust was measured during these tests and the O_2-fuel ratio calculated by the procedure outlined previously. These data are given in Table 24 and illustrated in Figures 44 and 45 for needle and low-sac injectors, respectively. The test points at which smoke opacity exceeded the baseline limit were enumerated in the preceding discussion. If a horizontal line is drawn on the two figures so that these test points lie below it, it is found that the line represents an

TABLE 23. MODAL SMOKE OPACITY FOR NEEDLE-VALVE AND LOW-SAC INJECTORS, STANDARD TIMING, AND HOT EGR

Mode	Notch Position	Engine Speed, rpm	PHS Smoke Opacity, % 0% EGR*	10%*	20%*	30%*
	Needle Injectors					
1, 6, 11	Low Idle	285	0.8	1.2	1.3	1.1
2	1	285	1.4	1.6	1.3	1.6
3	2	344	1.5	1.8	1.2	1.5
4	3	424	1.9	2.0	1.3	1.5
5	4	515	1.7	2.5	2.0	2.5
7	5	584	1.4	2.0	2.3	3.2
8	6	675	1.8	2.8	4.5	7.0
9	7	755	2.6	4.5	9.8	25.0
10	8	835	4.6	12.0	27.5	59.0
	Low-Sac Injectors					
1, 6, 11	Low Idle	285	1.0	-	1.0	1.3
2	1	285	1.2	-	1.0	1.5
3	2	344	1.2	-	2.0	2.2
4	3	424	1.3	-	1.5	2.0
5	4	515	2.3	-	2.0	3.5
7	5	584	1.8	-	2.0	4.2
8	6	675	2.1	-	3.0	6.5
9	7	755	2.5	-	7.0	25.0
10	8	835	3.8	-	22.0	54.5

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*Percent of engine air flow mass requirement per mode.

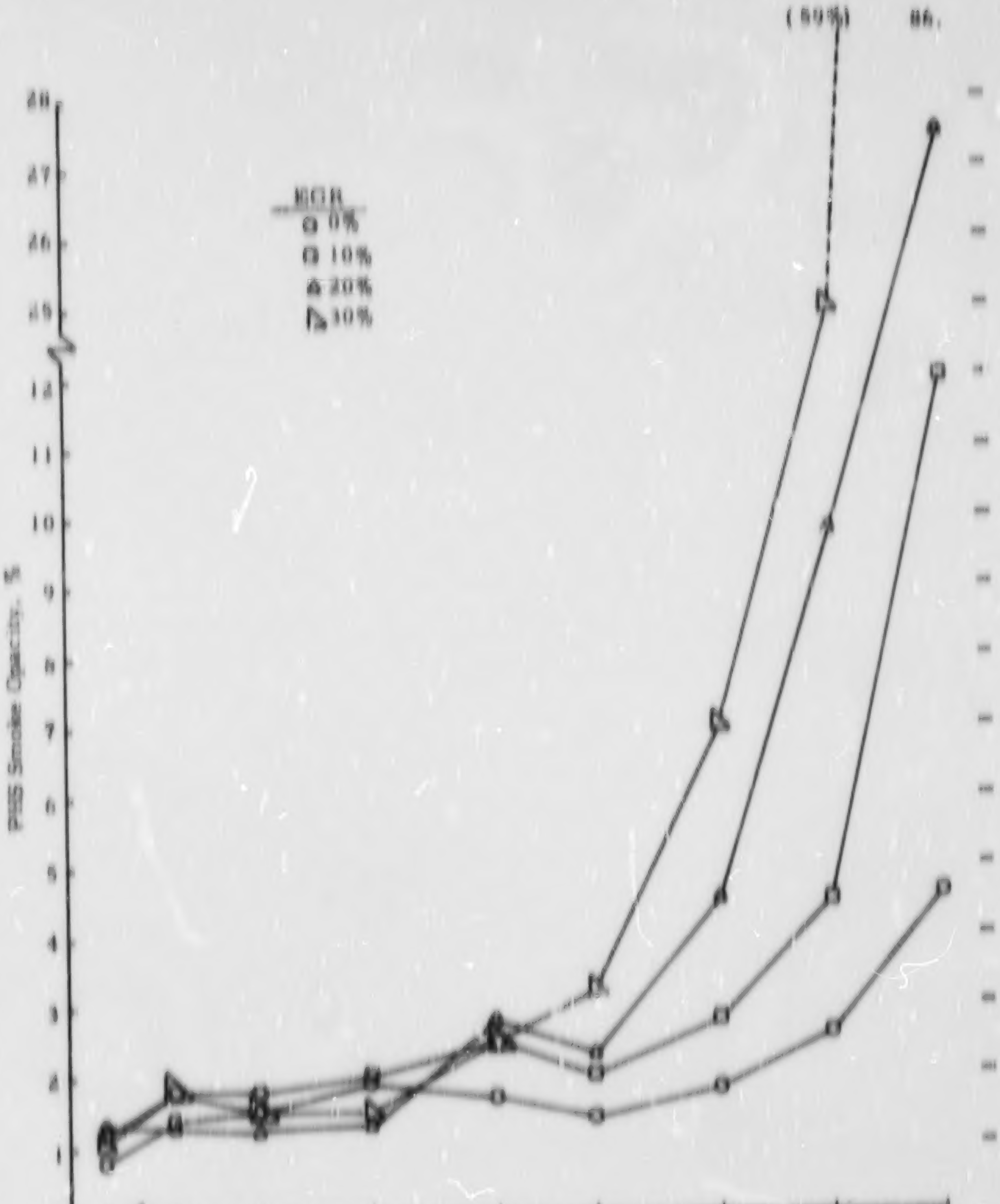

FIGURE 42. MODAL SMOKE OPACITY LEVELS FOR VARIOUS RATES OF HOT EGR--NEEDLE-VALVE INJECTORS AT STANDARD TIMING

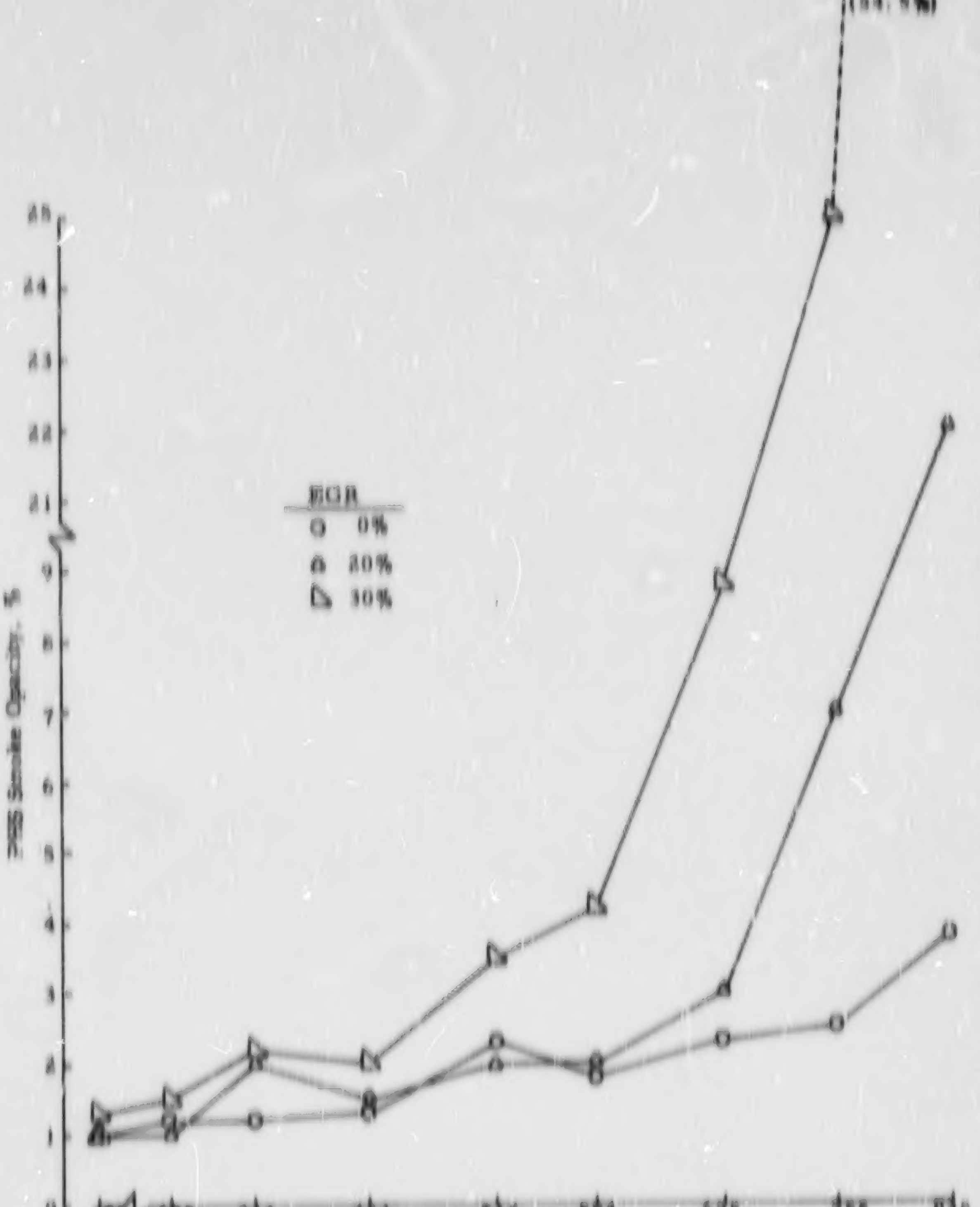

FIGURE 41. MODAL SMOKE OPACITY LEVELS FOR VARIOUS RATES OF HOT EGR--LOW-SAC INJECTORS AT STANDARD TIMING

TABLE 24. EXCESS O_2 CONCENTRATIONS AND O_2-FUEL RATIOS FOR HOT EGR--NEEDLE-VALVE AND LOW-SAC INJECTORS AT STANDARD TIMING

Notch Position	0% EGR		10% EGR		20% EGR		30% EGR	
	O_2, %	O_2/Fuel	O_2, %	O_2/Fuel	O_2, %	O_2/Fuel	O_2, %	O_2/Fuel
			Needle-Valve Injectors					
Low Idle	20.1	58.85	20.0	53.23	19.5	45.09	19.3	40.73
1	19.0	24.54	18.6	22.16	18.3	19.65	18.0	17.48
2	18.3	17.78	17.8	16.10	17.5	14.23	17.4	12.60
3	17.1	11.59	16.4	10.34	15.8	8.47	15.6	7.58
4	16.2	9.23	15.6	8.21	14.8	7.15	14.5	5.70
5	15.2	7.22	14.4	6.47	13.3	5.42	12.8	4.40
6	14.4	6.09	13.4	5.38	12.0	4.25	11.0	3.39
7	13.8	5.28	12.7	4.52	10.6	3.27	9.2	2.73
8	12.8	4.37	11.5	3.59	9.8	2.79	8.4	2.14
			Low-Sac Injectors					
Low Idle	20.2	57.56	°	°	19.5	50.59	19.6	47.20
1	19.4	25.22	°	°	18.6	20.56	18.5	17.78
2	18.8	18.85	°	°	18.2	15.41	18.0	13.40
3	17.7	12.78	°	°	16.5	9.79	16.0	8.32
4	17.1	10.46	°	°	15.4	7.51	14.8	6.62
5	15.9	8.14	°	°	14.0	5.89	12.9	4.81
6	15.2	6.93	°	°	12.7	4.68	11.1	3.80
7	14.6	6.07	°	°	11.4	3.77	9.4	2.92
8	13.8	5.09	°	°	10.1	2.95	8.6	2.37

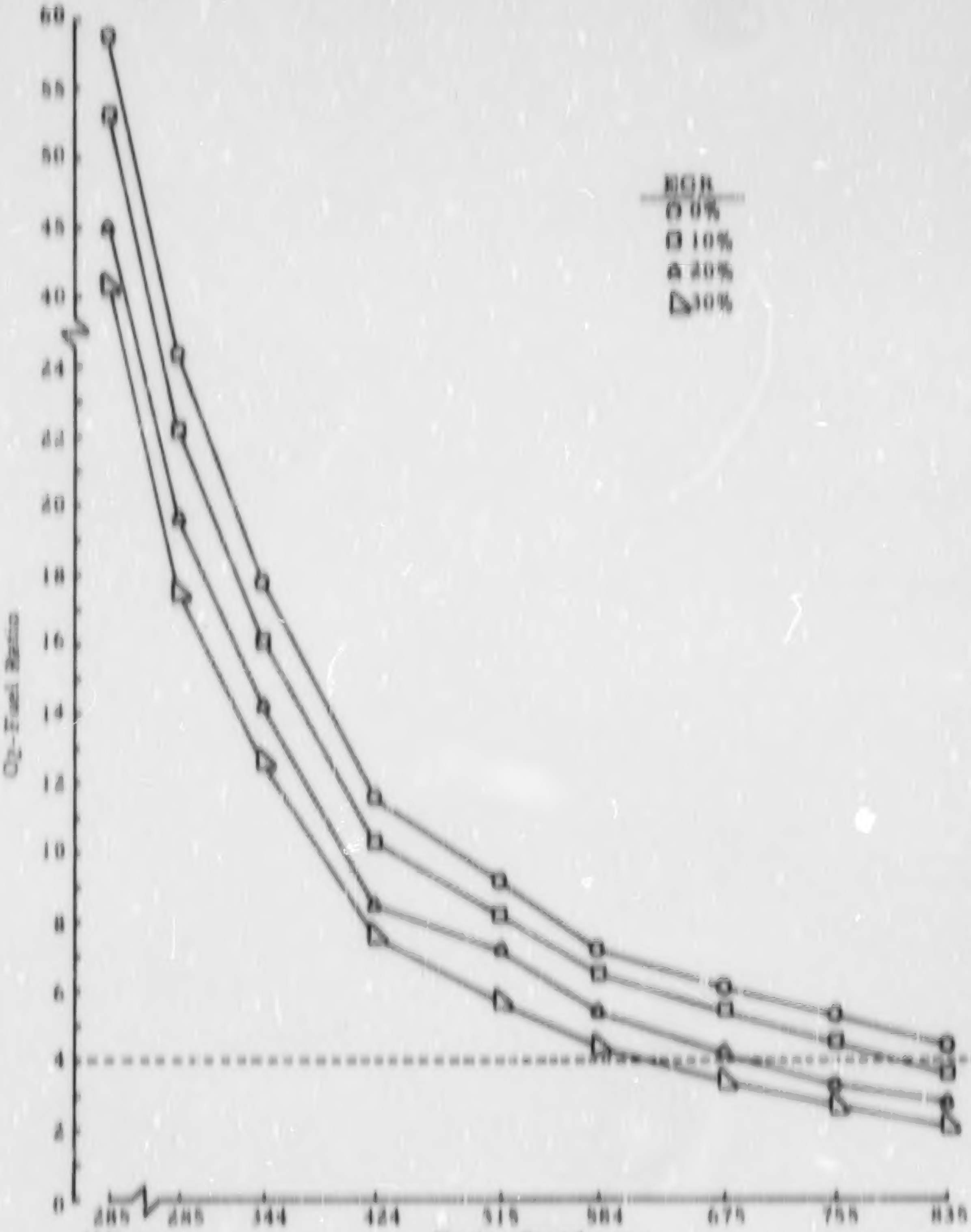

FIGURE 44. MODAL O$_2$-FUEL RATIOS FOR VARIOUS RATES OF HOT EGR--NEEDLE-VALVE INJECTORS AT STANDARD TIMING

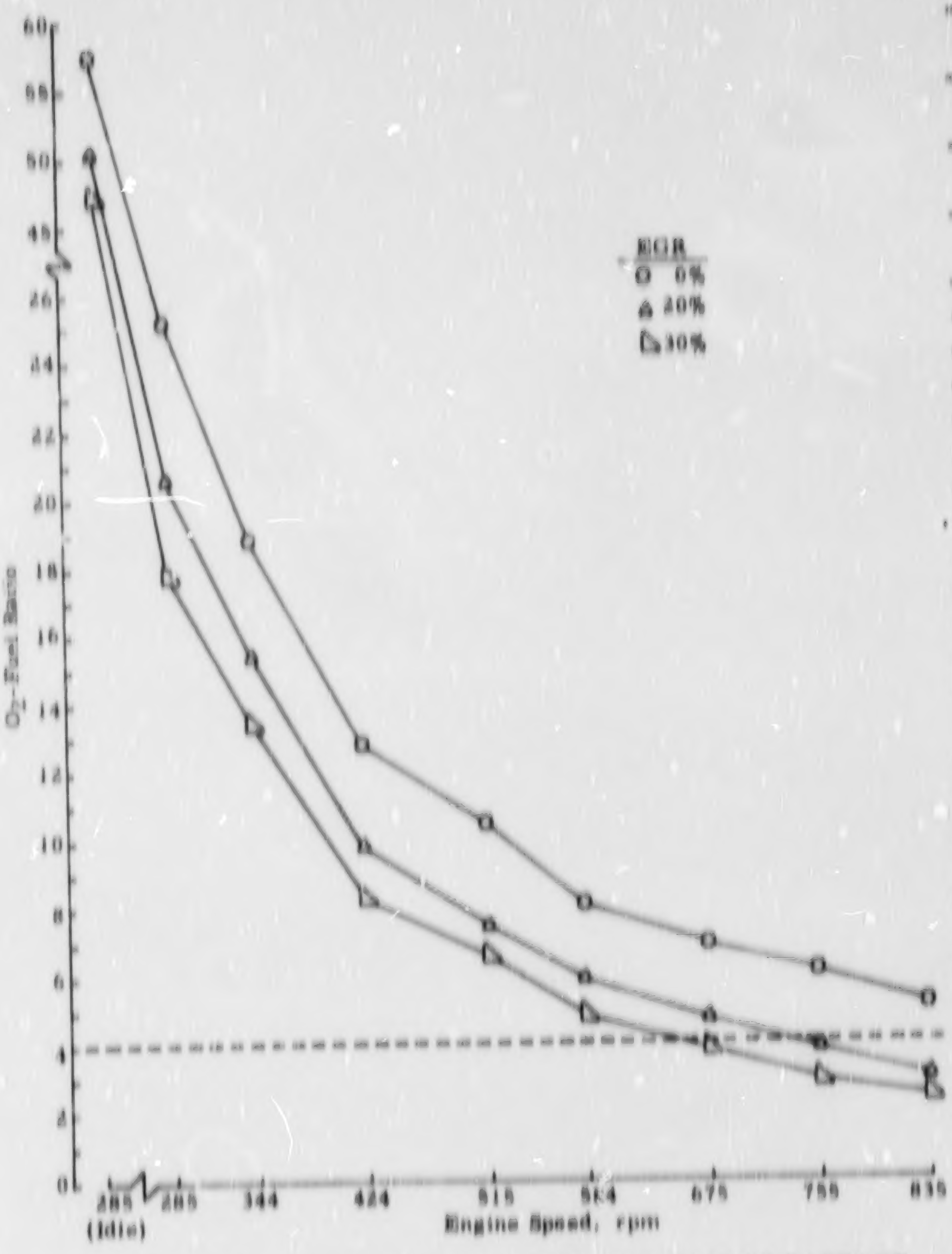

FIGURE 45. MODAL O_2-FUEL RATIOS FOR VARIOUS RATES OF HOT EGR—LOW-SAC INJECTORS AT STANDARD TIMING

O_2-fuel ratio of approximately 4.0. This same ratio was found to be of similar significance in tests with cooled EGR. However, the amount of excess O_2 present was considerably less with hot EGR than with cooled EGR. Thus, the O_2-fuel ratios for hot EGR are lower than the corresponding ratios found with cooled EGR, especially at the high-power notch position. Hence, hot EGR produced considerably more smoke at these points than did cooled EGR. Reduced charge density with "hot" EGR is one reason for the deterioration in smoke.

Engine power was derated with the low-sac injectors in an attempt to reduce smoke to the baseline limit. (A similar derating was inadvertently omitted during tests with the needle injectors.) The consequences of this derating are summarized in Table 25. The computer printouts for these tests are Tables B-185 through B-188 of Appendix B.

As in the other tests involving derating, it was found that HC and NO_x increased, while CO was reduced tremendously. The excess O_2-fuel ratio increased into the range of 4.7 to 5.8, which is considerably higher than the range of the corresponding ratios for cooled EGR. As mentioned previously, hot EGR produced smoke of much higher opacity than did cooled EGR, and the amount of power derating needed with hot EGR reflects the difference. With 20 percent EGR the power in notches 7 and 8 was reduced by 7 and 13 percent, respectively. This compares favorably to the derating needed with cooled EGR. However, with 30 percent hot EGR the power in these same notch positions was reduced by 24 and 37 percent, respectively. This is much greater than the corresponding power reductions of 13 and 14 percent required with cooled EGR.

The modal brake specific and fuel specific data for tests sans derating are presented in Table C-17 and Figures C-79 through C-84 for needle injectors and in Table C-18 and Figures C-85 through C-89 for low-sacs. In general, HC was slightly reduced by the use of hot EGR, but CO experienced the expected large increase, especially at the higher-power conditions. However, NO_x was reduced more in the upper notch positions than at the low end of the operating cycle. Even with these large reductions of NO_x, it is not likely that the very high smoke and CO output could be tolerated in actual locomotive operation.

The test engine showed poor operating characteristics with hot EGR. Such problems as unstable speed and load were experienced, especially in the higher notch positions, and these problems became worse as the EGR rate was increased. Output of particulate matter was apparently increased, as the filters used to remove such matter from the exhaust sample required frequent replacement during these tests. Engine power was reduced 15 to 20 percent at most points of the test cycle with nominal 30 percent EGR. These losses in observed power are three to four times greater than noted with cooled EGR.

TABLE 25. EFFECT OF DERATING ON EMISSIONS, SMOKE, AND POWER--LOW-SAC INJECTORS, STANDARD TIMING, AND HOT EGR

EGR Rate, %*	Cycle Composite Emissions BSHC Normal	BSHC Derate	BSCO Normal	BSCO Derate	$BSNO_x$ Normal	$BSNO_x$ Derate
20	0.473	0.496	33.357	6.886	5.249	6.713
30	0.600	0.710	64.156	2.242	4.128	7.088

EGR Rate, %*	Notch Position	Modal Emissions, Smoke, and Power BSHC Normal	BSHC Derate	BSCO Normal	BSCO Derate	$BSNO_x$ Normal	$BSNO_x$ Derate
20	7	0.36	0.40	16.21	7.94	5.45	5.90
	8	0.43	0.46	42.73	7.98	4.19	6.03
30	6	0.50	0.45	9.49	2.87	4.81	5.17
	7	0.50	0.60	34.12	2.78	3.45	5.43
	8	0.55	0.68	82.51	2.24	3.03	6.56

EGR Rate, %*	Notch Position	FSHC Normal	FSHC Derate	FSCO Normal	FSCO Derate	$FSNO_x$ Normal	$FSNO_x$ Derate
20	7	1.09	0.88	35.20	17.52	11.83	13.01
	8	0.81	0.96	80.91	16.53	7.91	12.50
30	6	1.13	1.02	21.21	6.56	10.79	11.77
	7	1.02	1.26	69.75	5.80	7.05	11.31
	8	1.00	1.28	149.01	2.38	5.46	12.33

EGR Rate, %*	Notch Position	O2-Fuel Ratio Normal	O2-Fuel Ratio Derate	Smoke, % Normal	Smoke, % Derate	Power, Bhp Normal	Power, Bhp Derate
20	7	3.77	4.93	7.0	4.5	165	154
	8	2.95	5.30	22.0	5.0	178	155
30	6	3.80	4.72	8.8	5.0	134	118
	7	2.92	5.03	25.0	5.8	154	117
	8	2.37	5.79	54.5	4.5	169	106

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*Percent of engine air flow mass requirement per mode.

H. Recheck of Baseline Emission Levels--Needle-Valve and Low-Sac Injectors at Standard Timing

The baseline emission levels presented in Part A of this section were checked at the end of the test series with needle and low-sac injectors. The results of these tests showed that the baseline for the needle injectors was about ten percent lower for HC and NO_x than at the beginning of the project. Smoke opacity and CO were nearly unchanged. The baseline for the low-sac injectors was almost identical with that which existed originally. This final baseline test series served to validate the experiments conducted with various control strategies and indicates the stability of the laboratory engine employed.

VI. SUMMARY AND CONCLUSIONS

This project was conducted for the purpose of evaluating several methods of controlling oxides of nitrogen and smoke output from a two-cylinder version of a popular locomotive engine. The effects of these control methods on hydrocarbon and carbon monoxide emissions were also to be determined. Several well-known methods of NO_x control--such as use of fuel injectors of different designs, variation of injection timing, inlet air humidification, reduction of scavenging air volume, and exhaust gas recirculation--were applied to the test engine. Results of the tests conducted with these control methods were then compared with results of a series of baseline tests, and the comparative effectiveness of the control methods determined.

The following conclusions were drawn from the results of the items of work mentioned above:

(1) Hydrocarbons (HC) were reduced substantially by merely changing from the older-style spherical-valve injectors to the newer needle-valve injectors. Another substantial reduction in HC occurred when the needle-valve injectors were replaced by the new low-sac models. Carbon monoxide (CO) was influenced to some extent by injector design, but the resulting levels were low in any case. Oxides of nitrogen (NO_x) were increased by the low-sac injectors over the levels produced by the other two types of injectors. This increase was most noticeable in the lower notch positions. Smoke opacity was very low in all tests, regardless of the type of injector used. Observed engine power was also approximately equal for each injector.

(2) Retarding the injection timing 4° from the standard setting resulted in slight reductions in HC and a substantial increase in CO in the upper notch positions. Oxides of nitrogen were reduced considerably throughout the test cycle. Smoke opacity was increased, particularly in the higher notch positions, but it was possible to reduce smoke to the baseline level with a slight derating of engine power. Without derating, engine power was not adversely affected by retarded timing. If injection was advanced 4° from the standard setting, HC, CO, and smoke opacity were reduced, but NO_x was increased.

(3) Water induction (inlet air humidification) was responsible for moderate reductions in NO_x, with little or no increases in HC, CO, and smoke opacity. The higher water rates (equal to 75 or 100 percent of fuel flow mass per mode) were most effective in reducing NO_x. Engine power was not adversely affected by the addition of water. One drawback of water induction as a control technique was the discovery that some of the water inducted did not remain in the intake air, but rather collected in the bottom of the engine air box. It is possible, of course, that this problem could be resolved by use of a different method of water atomization.

(4) When retarded injection timing and water induction were combined as a control method, it was found that NO_x was reduced by a greater amount than that observed for each method by itself. However, retarded timing was responsible for well over one-half of the reduction in NO_x. Also, CO and smoke opacity were higher in the upper notch positions than found to occur with retarded timing alone. A slight derating of engine power in these notches would no doubt reduce smoke to nominal baseline levels; however, this approach was not actually tried.

(5) Air box bleed (reduction of scavenging air volume) reduced HC with the needle injectors, but not with the low-sac models. Carbon monoxide was greatly increased in the high power conditions for both types of injectors. Brake specific NO_x values were lowered little or not at all, and the reductions which were observed were due, in the main, to the reduced mass flow of exhaust caused by venting the air box. Substantial reductions in the measured concentrations of NO_x did result from air box bleed, but these lower concentrations were in most cases offset by sharp reductions in power. Smoke opacity was greatly increased, and a substantial amount of power derating was needed to lower these opacities back to nominal baseline levels. Engine operation became rough and unstable if over 20 percent of the intake air mass was bled from the air box.

(6) Cooled EGR generally reduced HC or, at worst, produced only a small increase. Carbon monoxide was relatively unchanged at the low-power notch positions, but was substantially increased at the high-power conditions. Oxides of nitrogen showed very worthwhile reductions under all conditions, but especially in the higher notch positions. Smoke opacity was increased, but was deemed excessive only in the last two notches. Smoke opacity (and CO) could be reduced to baseline values by derating engine power. The amount of derating needed was very high for needle injectors, but more reasonable for the low-sac models. Derating caused NO_x to increase slightly and thus negated, to some extent, the beneficial effect of cooled EGR.

(7) Hot EGR resulted in lower HC in most instances, particularly with the needle injectors, but CO was increased tremendously in the upper notch positions. Oxides of nitrogen were reduced substantially, with the greatest decrease noted in the high-power conditions. Smoke opacity was extremely high in notch 8 and excessive in notch 7, as well. To reduce the smoke to baseline values required power to be derated by 24 and 37 percent, respectively, in notches 7 and 8 (30 percent EGR rate). Much less derating was needed with 20 percent EGR, but this lower rate did not produce as great a reduction in NO_x as the 30 percent rate. Hot EGR also resulted in rough engine operation and lower power in all notch positions.

(8) It is apparent that smoke opacity is highly sensitive to the oxygen-fuel ratio. This finding implies that any control technique which lowers this ratio below a definite point (about 4.0, in this instance) will cause "excessive" smoke - - i.e., smoke opacity beyond some agreed-upon level. Since air box bleed and EGR often reduce this ratio below the critical point, their use necessarily entails a reduction in fuel rate and, consequently, in engine power output. A sufficient reduction must be performed to cause the O_2-fuel ratio to return to the critical point previously established.

(9) Based on the above observations, it appears that for this particular case- - i.e., a two-cylinder version of a full-size locomotive engine- -the overall most effective control technique consisted of retarded injection timing, with a slight power derating to control smoke opacity. These were very simple steps to take, yet they resulted in a substantial reduction in NO_x, regardless of the type of injector used. The next most effective control method was cooled EGR, plus power derating to keep smoke and CO to acceptable levels. The observed reductions in NO_x were much greater with cooled EGR than with retarded timing, but the hardware required for use of cooled EGR on a full-size engine would be expensive and complicated.

LIST OF REFERENCES

1. Hare, Charles T., and Karl J. Springer, "Exhaust Emissions From Uncontrolled Vehicles and Related Equipment Using Internal Combustion Engines," Final Report (Part I) on locomotive diesel engines and marine counterparts, prepared for the Environmental Protection Agency, October 1972.

2. "A Progress Report On Electro-Motive's Emission Reduction Program for Diesel Engines," published by Electro-Motive Division of General Motors Corporation, September 1972.

3. *Federal Register*, Volume 37, No. 175 (Part II), p. 1870, September 8, 1972.

4. Report on Exhaust Emissions of Selected Railroad Diesel Locomotives, prepared by Southern Pacific Transportation Company, March 1972.

5. Unconfirmed Minutes of a meeting of The Large Engine Diesel Smoke Procedure Task Force, April 18, 1973.

6. Hare, op. cit., p. 20.

7. Springer, Karl J., "An Investigation of Diesel-Powered Vehicle Odor and Smoke--Part V," prepared for the Environmental Protection Agency, to be published Fall, 1973.

APPENDIX A

Letter from Hugh A. Williams, Jr., of EMD to Karl J. Springer, Manager Emissions Research Laboratory

ELECTRO-MOTIVE DIVISION
GENERAL MOTORS CORPORATION
LA GRANGE ILLINOIS

August 8, 1972

Mr. Karl J. Springer, Manager
Emissions Research Laboratory
Southwest Research Institute
8500 Culebra Road
P. O. Drawer 28510
San Antonio, Texas 78284

Dear Karl,

In reply to your letter of July 24, 1972 relative to possible configurations of your 2-567 engine for emissions tests, we would offer the following information:

Model 2-567C Engine

Part No.	*Name*	*Description*
8500780	Cyl. Liner	Basic 567 20-port liner
8409499	Piston	Basic 567C with trunnion type connection rod (*16:1 compression ratio*)
or		
8061362	Piston	Basic 567B with floating type rod (*16:1 compression ratio*)
5228230	Injector	567C Basic, Spherical valve, medium output
or		
5227852	Injector	567B Basic, Spherical valve, low output

The aforementioned part numbers should permit you to identify the parts in your engine. Injectors which were basic to either the 567C or 567B are listed above. The 567C needle valve injectors with 5228713 spray tips which you have in your engine now are standard needle valve tips in the medium air flow range. The needle valve spray tip for the 567 series engine is available in the low, medium, and high air flow range (*corresponding to orifice area*) and permits the customer who calibrates his own injectors to select the correct spray tip to provide the required injector calibration.

For baseline tests, you could use the 5228230 spherical valve injector, follow it up with the needle valve injector 5228800 (*UTEX #[illegible] with calibrating slide or UTEX #[illegible] without calibrating slide*), equipped with the 5228713 medium air flow tip.

For a third injector configuration we will provide you with two new injector assemblies 5230290, equipped with 5229243 spray tips. These tips are similar to the 5228713 in that they are medium air flow; however, they have a 53% reduction in the fuel sac volume between the needle valve seat and the orifices.

Basic injector timing for all Roots blown EMD engines is 4° BTC. You may advance timing to approximately 10° BTC before the tappet goes solid against the injector body at the bottom of the stroke and you may retard timing to approximately 4° ATC before the little spherical button retaining spring on the injector adjusting screw is jammed up under the injector rocker arm, causing the spring to break. Thus, you have the latitude of +6 degrees or -8 degrees of adjustment at your disposal. You can probably limit this to ± 4 degrees for practical purposes; i.e., 4 degrees advanced will create excessive rates of pressure rise during combustion and 4 degrees retarded will give you plenty of smoke -- probably more than you can tolerate.

Relative to the type of duty cycle you are planning to use, I have enclosed a chart of the speeds versus throttle position for the 567B and C engines. Also enclosed is a table of Representative EMD Engine Exhaust Flow and Fuel Rates vs. Throttle Position which I had previously sent to you. Also included is a chart of Power piston gap -- fuel output comparison which should be helpful to you in comparing power piston gap versus injector rack length for both the 567B injector 5227852 and 567C injector 5228230.

I will not attempt to provide you with governor power piston gap settings for each throttle position for a 567C engine.

Perhaps your idea of setting fuel rates at each throttle would be equally satisfactory. If you wish us to confirm any engine settings or representative values which you plan to use, please let us know.

Best wishes,

Hugh

H. A. WILLIAMS, JR.
ENGINEERING DEPARTMENT
Engine Design Section

HAW/ar

cc: J. J. Koffin
W. K. Sampson

File: E-17-A

APPENDIX B

Computer Printouts of Tests Data and Results

Emission Concentration and Rate Summary

TABLE B-[illegible]: EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

TABLE B-[illegible]: EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

TABLE B-[illegible]: EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

CYCLE COMPOSITE [illegible]

TABLE B-[illegible]: EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

CYCLE COMPOSITE [illegible]

TABLE [illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

CYCLE COMPOSITE [illegible]

TABLE [illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

CYCLE COMPOSITE [illegible]

TABLE [illegible] EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

TABLE [illegible] EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

TABLE B-9. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

TABLE B-10. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

TABLE B-11. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

TABLE B-12. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

TABLE D-13. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

TABLE D-14. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

TABLE [illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

TABLE [illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

TABLE B-17. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

CYCLE COMPOSITE [illegible]

[illegible]

TABLE B-18. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

CYCLE COMPOSITE [illegible]

[illegible]

TABLE B-17. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

TABLE B-18. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

TABLE B-[illegible]: EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

CYCLE COMPOSITE [illegible]

TABLE B-[illegible]: EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

CYCLE COMPOSITE [illegible]

TABLE 5-[illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

CYCLE COMPOSITE [illegible]

TABLE 5-[illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

CYCLE COMPOSITE [illegible]

TABLE B-[illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

TABLE B-[illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

TABLE B-37. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

CYCLE COMPOSITE [illegible]

TABLE B-38. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

CYCLE COMPOSITE [illegible]

TABLE B-19. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

[illegible]

CYCLE COMPOSITE [illegible]

[illegible]

TABLE B-20. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

[illegible]

CYCLE COMPOSITE [illegible]

[illegible]

TABLE B-11: EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

CYCLE COMPOSITE [illegible]

TABLE B-11: EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

CYCLE COMPOSITE [illegible]

TABLE B-[illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

CYCLE COMPOSITE [illegible]

TABLE B-[illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

CYCLE COMPOSITE [illegible]

TABLE B-15 EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

CYCLE COMPOSITE [illegible]

TABLE B-16. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

CYCLE COMPOSITE [illegible]

TABLE B-17. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

CYCLE COMPOSITE [illegible]

TABLE B-18. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

CYCLE COMPOSITE [illegible]

TABLE B-[illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

CYCLE COMPOSITE

[illegible]

TABLE B-[illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

CYCLE COMPOSITE

[illegible]

TABLE B-[illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

TABLE B-[illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

TABLE B-[illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

[illegible]

CYCLE COMPOSITE [illegible]

TABLE B-[illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

% OXYGEN [illegible] IN EXHAUST   APPARENT [illegible] AIR FUEL RATIO

[illegible]

CYCLE COMPOSITE [illegible]

TABLE B-39. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

[illegible]

CYCLE COMPOSITE [illegible]

TABLE B-40. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

[illegible]

CYCLE COMPOSITE [illegible]

TABLE B-47. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

TABLE B-48. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

TABLE [illegible] EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

[illegible]

* PERCENT OF FUEL FLOW RATE

[illegible]

CYCLE COMPOSITE [illegible]

TABLE [illegible] EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

[illegible]

* PERCENT OF FUEL FLOW RATE

[illegible]

CYCLE COMPOSITE [illegible]

TABLE [illegible] EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

PERCENT OF FUEL FLOW RATE

[illegible]

CYCLE COMPOSITE [illegible]

TABLE [illegible] EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

PERCENT OF FUEL FLOW RATE

[illegible]

CYCLE COMPOSITE [illegible]

TABLE D-[illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

PERCENT OF FUEL FLOW RATE

[illegible]

CYCLE COMPOSITE

[illegible]

TABLE D-[illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

PERCENT OF FUEL FLOW RATE

[illegible]

CYCLE COMPOSITE

[illegible]

TABLE [illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

* PERCENT OF FUEL FLOW RATE

[illegible]

CYCLE COMPOSITE [illegible]

TABLE [illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

* PERCENT OF FUEL FLOW RATE

[illegible]

CYCLE COMPOSITE [illegible]

TABLE B-[illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible] PERCENT RATED

[illegible]

* PERCENT OF FUEL FLOW MASS

[illegible]

CYCLE COMPOSITE [illegible]

TABLE B-[illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible] PERCENT RATED

[illegible]

* PERCENT OF FUEL FLOW MASS

[illegible]

CYCLE COMPOSITE [illegible]

TABLE [illegible] EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

% PERCENT OF FUEL FLOW RATE

[illegible]

CYCLE COMPOSITE

[illegible]

TABLE [illegible] EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

% PERCENT OF FUEL FLOW RATE

[illegible]

CYCLE COMPOSITE

[illegible]

TABLE [illegible] EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

% EXCESS O2 IN EXHAUST **PERCENT OF FUEL FLOW MASS

[illegible]

CYCLE COMPOSITE [illegible]

TABLE [illegible] EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

% EXCESS O2 IN EXHAUST **PERCENT OF FUEL FLOW MASS

[illegible]

CYCLE COMPOSITE [illegible]

TABLE B-[illegible]. EMISSIONS CONCENTRATION AND RATE SUMMARY

[illegible]

CYCLE COMPOSITE [illegible]

TABLE B-[illegible]. EMISSIONS CONCENTRATION AND RATE SUMMARY

[illegible]

CYCLE COMPOSITE [illegible]

TABLE [illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

TABLE [illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

TABLE [illegible] EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

TABLE [illegible] EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

TABLE B-[illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

PERCENT OF FUEL FLOW MASS

[illegible]

CYCLE COMPOSITE

[illegible]

TABLE B-[illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

PERCENT OF FUEL FLOW MASS

[illegible]

CYCLE COMPOSITE

[illegible]

TABLE B-71. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

* PERCENT OF FUEL FLOW RATE

[illegible]

CYCLE COMPOSITE [illegible]

BSHC = [illegible]

TABLE B-72. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

* PERCENT OF FUEL FLOW RATE

[illegible]

CYCLE COMPOSITE [illegible]

BSHC = [illegible]

TABLE B-13. EMISSIONS CONCENTRATION AND RATE SUMMARY

[illegible]

PERCENT OF FUEL FLOW MASS

[illegible]

CYCLE COMPOSITE [illegible]

TABLE B-14. EMISSIONS CONCENTRATION AND RATE SUMMARY

[illegible]

PERCENT OF FUEL FLOW MASS

[illegible]

CYCLE COMPOSITE [illegible]

TABLE [illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible] PERCENT RATED

[illegible]

[illegible] PERCENT OF FUEL FLOW RATE

[illegible]

CYCLE COMPOSITE [illegible]

[illegible] = [illegible]

TABLE [illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible] PERCENT RATED

[illegible]

[illegible] PERCENT OF FUEL FLOW RATE

[illegible]

CYCLE COMPOSITE [illegible]

[illegible] = [illegible]

TABLE D-17. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

TABLE D-18. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

TABLE B-79. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

* PERCENT OF FUEL FLOW RATE

[illegible]

CYCLE COMPOSITE [illegible]

TABLE B-80. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

* PERCENT OF FUEL FLOW RATE

[illegible]

CYCLE COMPOSITE [illegible]

TABLE B-[illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

[illegible] IN EXHAUST [illegible] PERCENT OF FUEL FLOW RATE

CYCLE COMPOSITE

[illegible]

TABLE B-[illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

[illegible] IN EXHAUST [illegible] PERCENT OF FUEL FLOW RATE

CYCLE COMPOSITE

[illegible]

TABLE [illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

% EXCESS O2 IN EXHAUST   %PERCENT OF FUEL FLOW RATE

[illegible]

CYCLE COMPOSITE

[illegible]

TABLE [illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

% EXCESS O2 IN EXHAUST   %PERCENT OF FUEL FLOW RATE

[illegible]

CYCLE COMPOSITE

[illegible]

TABLE B-[illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

* EXCESS O2 IN EXHAUST **PERCENT OF FUEL FLOW MASS

[illegible]

CYCLE COMPOSITE

[illegible]

TABLE B-[illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

* EXCESS O2 IN EXHAUST **PERCENT OF FUEL FLOW MASS

[illegible]

CYCLE COMPOSITE

[illegible]

TABLE B-[illegible]. EMISSIONS CONCENTRATION AND RATE SUMMARY

[illegible]

TABLE B-[illegible]. EMISSIONS CONCENTRATION AND RATE SUMMARY

[illegible]

TABLE B-[illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

* PERCENT OF FUEL FLOW RATE

[illegible]

CYCLE COMPOSITE [illegible]

TABLE B-[illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

* PERCENT OF FUEL FLOW RATE

[illegible]

CYCLE COMPOSITE [illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

TABLE B-[illegible]. EMISSION CONCENTRATION AND [illegible] SUMMARY

[illegible]

[illegible]

* PERCENT OF FUEL FLOW RATE

[illegible]

CYCLE COMPOSITE [illegible]

TABLE B-[illegible]. EMISSION CONCENTRATION AND [illegible] SUMMARY

[illegible]

[illegible]

* PERCENT OF FUEL FLOW RATE

[illegible]

CYCLE COMPOSITE [illegible]

TABLE B-[illegible] EMISSIONS CONCENTRATION AND RATE SUMMARY

[illegible]

* PERCENT OF FUEL FLOW RATE

[illegible]

CYCLE COMPOSITE

[illegible]

TABLE B-[illegible]. EMISSIONS CONCENTRATION AND RATE SUMMARY

[illegible]

* PERCENT OF FUEL FLOW RATE

[illegible]

CYCLE COMPOSITE

[illegible]

TABLE [illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

* PERCENT OF FUEL FLOW MASS

[illegible]

CYCLE COMPOSITE [illegible]

TABLE [illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

* PERCENT OF FUEL FLOW MASS

[illegible]

CYCLE COMPOSITE [illegible]

TABLE B-99. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

TABLE B-100. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

TABLE B-[illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

TABLE B-[illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

TABLE D-[illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

[illegible]

% EXCESS O2 IN EXHAUST   1/PERCENT OF FUEL FLOW MASS

[illegible]

CYCLE COMPOSITE [illegible]

TABLE D-[illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

[illegible]

% EXCESS O2 IN EXHAUST   1/PERCENT OF FUEL FLOW MASS

[illegible]

CYCLE COMPOSITE [illegible]

TABLE B-[illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

[illegible] PERCENT OF AIR FLOW MODE

[illegible]

CYCLE COMPOSITE [illegible]

MODE [illegible]

TABLE B-[illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

[illegible] PERCENT OF AIR FLOW MODE

[illegible]

CYCLE COMPOSITE [illegible]

MODE [illegible]

TABLE B-[illegible] EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

[illegible]

PERCENT OF AIR FLOW MASS

[illegible]

CYCLE COMPOSITE

[illegible]

TABLE B-[illegible] EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

[illegible]

PERCENT OF AIR FLOW MASS

[illegible]

CYCLE COMPOSITE

[illegible]

TABLE B-10: EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

% PERCENT OF AIR FLOW MASS

[illegible]

CYCLE COMPOSITE

[illegible]

TABLE B-11: EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

% PERCENT OF AIR FLOW MASS

[illegible]

CYCLE COMPOSITE

[illegible]

TABLE B-111. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

[illegible]

* PERCENT OF AIR FLOW RATE

[illegible]

CYCLE COMPOSITE [illegible]

TABLE B-111. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

[illegible]

* PERCENT OF AIR FLOW RATE

[illegible]

CYCLE COMPOSITE [illegible]

TABLE D-[illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

[illegible]

CYCLE COMPOSITE [illegible]

[illegible]

TABLE D-[illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

[illegible]

CYCLE COMPOSITE [illegible]

[illegible]

TABLE [illegible] EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

CYCLE COMPOSITE

[illegible]

TABLE [illegible] EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

CYCLE COMPOSITE

[illegible]

TABLE B-117. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

TABLE B-118. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

TABLE B-[illegible] EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

1 PERCENT OF AIR FLOW RATE

[illegible]

CYCLE COMPOSITE

MODE [illegible]

TABLE B-[illegible] EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

1 PERCENT OF AIR FLOW RATE

[illegible]

CYCLE COMPOSITE

MODE [illegible]

TABLE B-[illegible] EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

[illegible]

CYCLE COMPOSITE [illegible]

TABLE B-[illegible] EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

[illegible]

CYCLE COMPOSITE [illegible]

TABLE B-1[illegible] EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

[illegible]

% PERCENT OF AIR FLOW RATE

[illegible]

CYCLE COMPOSITE

[illegible]

TABLE B-1[illegible] EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

[illegible]

% PERCENT OF AIR FLOW RATE

[illegible]

CYCLE COMPOSITE

[illegible]

TABLE [illegible] EMISSIONS CONCENTRATION AND RATE SUMMARY

[illegible]

[illegible] EXHAUST [illegible]

CYCLE COMPOSITE [illegible]

TABLE [illegible] EMISSIONS CONCENTRATION AND RATE SUMMARY

[illegible]

[illegible] EXHAUST [illegible]

CYCLE COMPOSITE [illegible]

TABLE B-111. EMISSIONS CONCENTRATION AND RATE SUMMARY

[illegible]

TABLE B-111. EMISSIONS CONCENTRATION AND RATE SUMMARY

[illegible]

TABLE B-1[illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

% EXCESS O2 IN EXHAUST   %PERCENT OF AIR FLOW RATE

[illegible]

TABLE B-1[illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

% EXCESS O2 IN EXHAUST   %PERCENT OF AIR FLOW RATE

[illegible]

TABLE B-111 EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

CYCLE COMPOSITE

[illegible]

TABLE B-111 EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

CYCLE COMPOSITE

[illegible]

TABLE B-[illegible] EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

CYCLE COMPOSITE [illegible]

TABLE B-[illegible] EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

CYCLE COMPOSITE [illegible]

TABLE B-[illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

TABLE B-[illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

TABLE B-[illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

TABLE B-[illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

TABLE B-[illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

TABLE B-[illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

TABLE B.[illegible] EMISSIONS CONCENTRATION AND RATE SUMMARY

[illegible]

TABLE B.[illegible] EMISSIONS CONCENTRATION AND RATE SUMMARY

[illegible]

TABLE B-[illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

CYCLE COMPOSITE

[illegible]

TABLE B-[illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

CYCLE COMPOSITE

[illegible]

TABLE B-105. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

TABLE B-106. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

TABLE B-[illegible] EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

CYCLE COMPOSITE [illegible]

TABLE B-[illegible] EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

CYCLE COMPOSITE [illegible]

TABLE B-[illegible] EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

[illegible]

% EXCESS O2 IN EXHAUST (PERCENT OF AIR FLOW RATE)

[illegible]

CYCLE COMPOSITE [illegible]

RATE : [illegible]

TABLE B-[illegible] EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

[illegible]

% EXCESS O2 IN EXHAUST (PERCENT OF AIR FLOW RATE)

[illegible]

CYCLE COMPOSITE [illegible]

RATE : [illegible]

TABLE B-[illegible]: EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

[illegible]

CYCLE COMPOSITE [illegible]

[illegible]

TABLE B-[illegible]: EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

[illegible]

CYCLE COMPOSITE [illegible]

[illegible]

TABLE B-[illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

% EXCESS O2 IN EXHAUST %PERCENT OF AIR FLOW MASS

[illegible]

CYCLE COMPOSITE

[illegible]

TABLE B-[illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

% EXCESS O2 IN EXHAUST %PERCENT OF AIR FLOW MASS

[illegible]

CYCLE COMPOSITE

[illegible]

TABLE B-155. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

TABLE B-156. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

TABLE B-[illegible] [illegible] CONCENTRATION AND MASS SUMMARY

[illegible]

MODE	[illegible]	POWER	FUEL	AIR	EXHAUST	[illegible]	[illegible]	[illegible]	TEMPERATURES	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

[illegible]

MODE	EXHAUST	HC	CO	[illegible]	[illegible]	[illegible]	CO2	O2	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

CYCLE COMPOSITE [illegible]

TABLE B-[illegible] [illegible] CONCENTRATION AND MASS SUMMARY

[illegible]

MODE	EXHAUST	POWER	FUEL	AIR	EXHAUST	[illegible]	[illegible]	[illegible]	TEMPERATURES	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

[illegible]

MODE	EXHAUST	HC	CO	[illegible]	[illegible]	[illegible]	CO2	O2	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

CYCLE COMPOSITE [illegible]

TABLE B-[illegible] EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

TABLE B-[illegible] EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

TABLE B-151 EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

CYCLE COMPOSITE

MODE : [illegible]

TABLE B-152 EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

CYCLE COMPOSITE

MODE : [illegible]

TABLE B-[illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

TABLE B-[illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

TABLE B-[illegible]. EMISSIONS CONCENTRATION AND RATE SUMMARY

[illegible]

* EXCESS O2 IN EXHAUST   #PERCENT OF AIR FLOW MASS

[illegible]

CYCLE COMPOSITE [illegible]

TABLE B-[illegible]. EMISSIONS CONCENTRATION AND RATE SUMMARY

[illegible]

* EXCESS O2 IN EXHAUST   #PERCENT OF AIR FLOW MASS

[illegible]

CYCLE COMPOSITE [illegible]

TABLE B-[illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

CYCLE COMPOSITE [illegible]

TABLE B-[illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

CYCLE COMPOSITE [illegible]

TABLE B-169. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

% EXCESS O2 IN EXHAUST   *PERCENT OF AIR FLOW MASS

[illegible]

CYCLE COMPOSITE [illegible]

BSNO = [illegible]

TABLE B-170 EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

% EXCESS O2 IN EXHAUST   *PERCENT OF AIR FLOW MASS

[illegible]

CYCLE COMPOSITE [illegible]

BSNO = [illegible]

TABLE B-111. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

TABLE B-112. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

TABLE B-113. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

CYCLE COMPOSITE

[illegible]

TABLE B-114. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

CYCLE COMPOSITE

[illegible]

TABLE [illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

% EXCESS O2 IN EXHAUST   *PERCENT OF AIR FLOW MASS

[illegible]

CYCLE COMPOSITE

[illegible]

TABLE [illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

% EXCESS O2 IN EXHAUST   *PERCENT OF AIR FLOW MASS

[illegible]

CYCLE COMPOSITE

[illegible]

TABLE B-177. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

CYCLE COMPOSITE

[illegible]

TABLE B-178. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

CYCLE COMPOSITE

[illegible]

TABLE B-[illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

TABLE B-[illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

TABLE [illegible] EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

[illegible] EXCESS O2 IN EXHAUST [illegible]PERCENT OF AIR FLOW MASS

[illegible]

CYCLE COMPOSITE [illegible]

TABLE [illegible] EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

[illegible] EXCESS O2 IN EXHAUST [illegible]PERCENT OF AIR FLOW MASS

[illegible]

CYCLE COMPOSITE [illegible]

TABLE [illegible] EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

MODE	[illegible]	POWER	[illegible]	[illegible]	EXHAUST	[illegible]	[illegible]	[illegible]	TEMPERATURES	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

[illegible] EXHAUST [illegible] OF AIR FLOW [illegible]

MODE	EXHAUST	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

CYCLE COMPOSITE [illegible]

TABLE [illegible] EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

MODE	[illegible]	POWER	[illegible]	[illegible]	EXHAUST	[illegible]	[illegible]	[illegible]	TEMPERATURES	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

[illegible] EXHAUST [illegible] OF AIR FLOW [illegible]

MODE	EXHAUST	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

CYCLE COMPOSITE [illegible]

TABLE B-[illegible]. EMISSION CONCENTRATIONS AND RATE SUMMARY

[illegible] HOT [illegible] FID [illegible]

[illegible]

% EXCESS O2 IN EXHAUST [illegible] PERCENT OF AIR FLOW MASS

[illegible]

CYCLE COMPOSITE [illegible]

TABLE B-[illegible]. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible] HOT [illegible] FID [illegible]

[illegible]

% EXCESS O2 IN EXHAUST [illegible] PERCENT OF AIR FLOW MASS

[illegible]

CYCLE COMPOSITE [illegible]

TABLE B-107. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

CYCLE COMPOSITE

[illegible]

TABLE B-108. EMISSION CONCENTRATION AND RATE SUMMARY

[illegible]

CYCLE COMPOSITE

[illegible]

APPENDIX C

Tables and Graphs of Modal Brake Specific Emissions Data

Tables and Graphs of Modal Fuel Specific Emissions Data

Tables and Graphs of Modal Emission Concentrations Data

TABLE C-[illegible]. MODAL BRAKE SPECIFIC AND FUEL SPECIFIC EMISSIONS FOR SPHERICAL-VALVE, NEEDLE-VALVE, AND LOW-SAC INJECTORS AT STANDARD TIMING

Mode	Engine Speed, rpm	Grams/Bhp-Hour HC	Grams/Bhp-Hour CO	Grams/Bhp-Hour NO_x	Grams/Pound of Fuel HC	Grams/Pound of Fuel CO	Grams/Pound of Fuel NO_x
Spherical Injectors							
1, 6, 11	285	*	*	*	7.61	3.56	11.15
2	285	6.88	4.66	15.58	9.55	3.78	12.77
3	344	4.74	2.79	11.85	8.66	3.33	14.20
4	424	3.32	1.14	10.62	5.90	2.03	18.87
5	515	2.58	0.76	11.17	5.73	1.55	22.45
7	584	2.57	0.86	12.04	5.45	1.81	25.55
8	675	2.65	1.16	12.48	5.77	2.51	27.16
9	755	2.60	2.40	12.08	5.55	5.12	25.74
10	835	2.29	7.42	11.64	4.76	15.45	24.21
Needle Injectors							
1, 6, 11	285	*	*	*	5.60	4.60	16.52
2	285	3.51	3.70	14.53	3.84	3.65	16.61
3	344	1.80	2.06	9.22	2.68	3.05	13.79
4	424	1.06	0.85	8.47	2.07	1.68	16.54
5	515	0.94	0.61	9.41	1.96	1.28	19.69
7	584	0.81	0.70	10.17	1.71	1.53	22.27
8	675	0.89	1.92	10.52	1.94	4.20	23.00
9	755	0.93	5.46	9.75	2.03	11.89	21.28
10	835	0.92	12.70	9.12	1.92	26.15	19.06
Low-Sac Injectors							
1, 6, 11	285	*	*	*	3.86	5.08	29.33
2	285	0.71	1.81	12.70	1.28	3.24	22.92
3	344	0.61	1.25	11.23	1.22	2.49	22.39
4	424	0.46	0.69	11.41	1.03	1.55	25.72
5	515	0.43	0.44	12.67	0.99	1.03	29.84
7	584	0.42	0.56	13.82	0.99	1.31	32.30
8	675	0.49	1.04	13.61	1.14	2.41	31.47
9	755	0.54	3.28	13.16	1.24	7.56	30.27
10	835	0.60	8.86	12.19	1.32	19.75	27.20

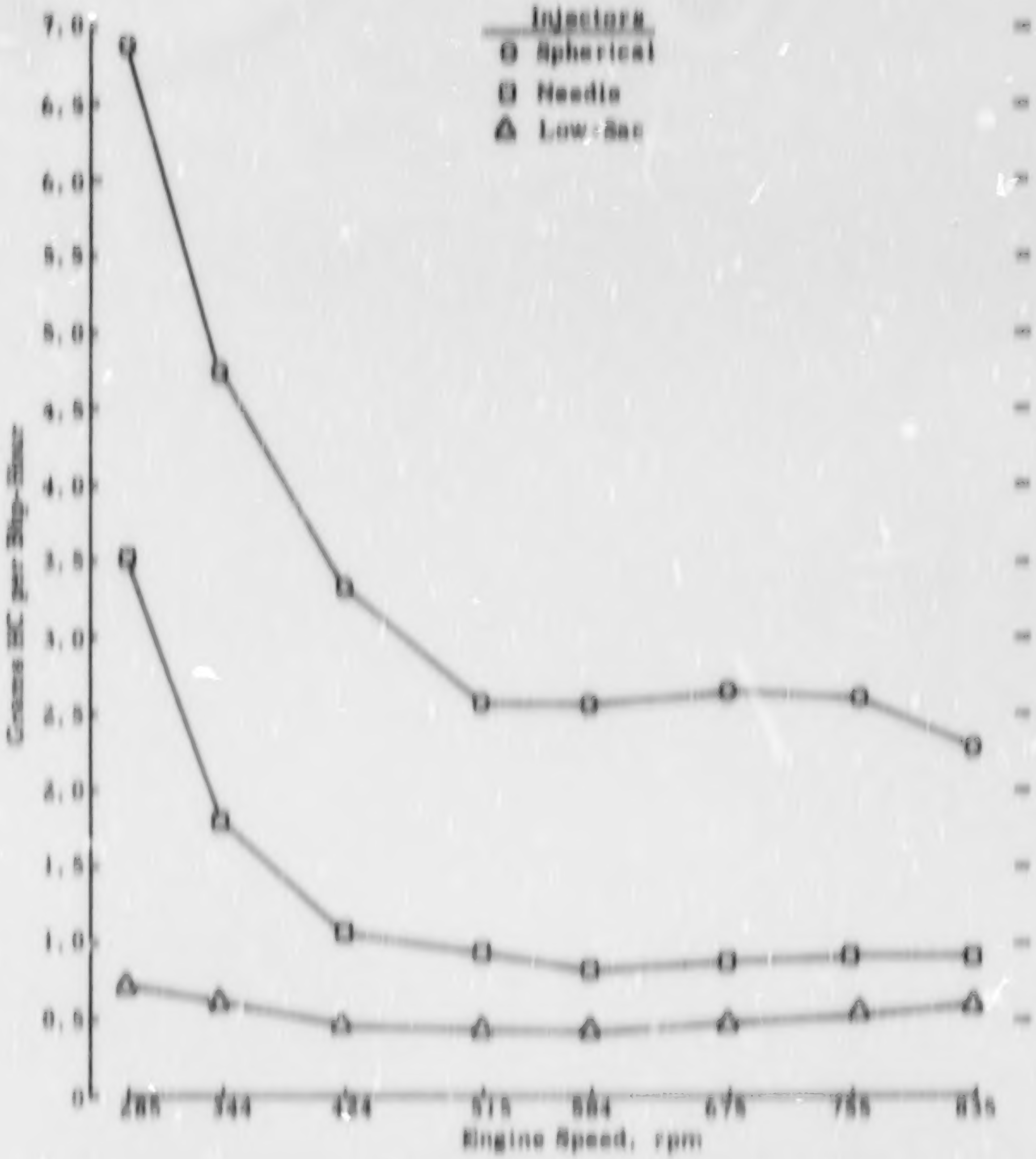

FIGURE C-1. MODAL BRAKE SPECIFIC HC FOR THREE TYPES OF FUEL INJECTORS AT STANDARD TIMING

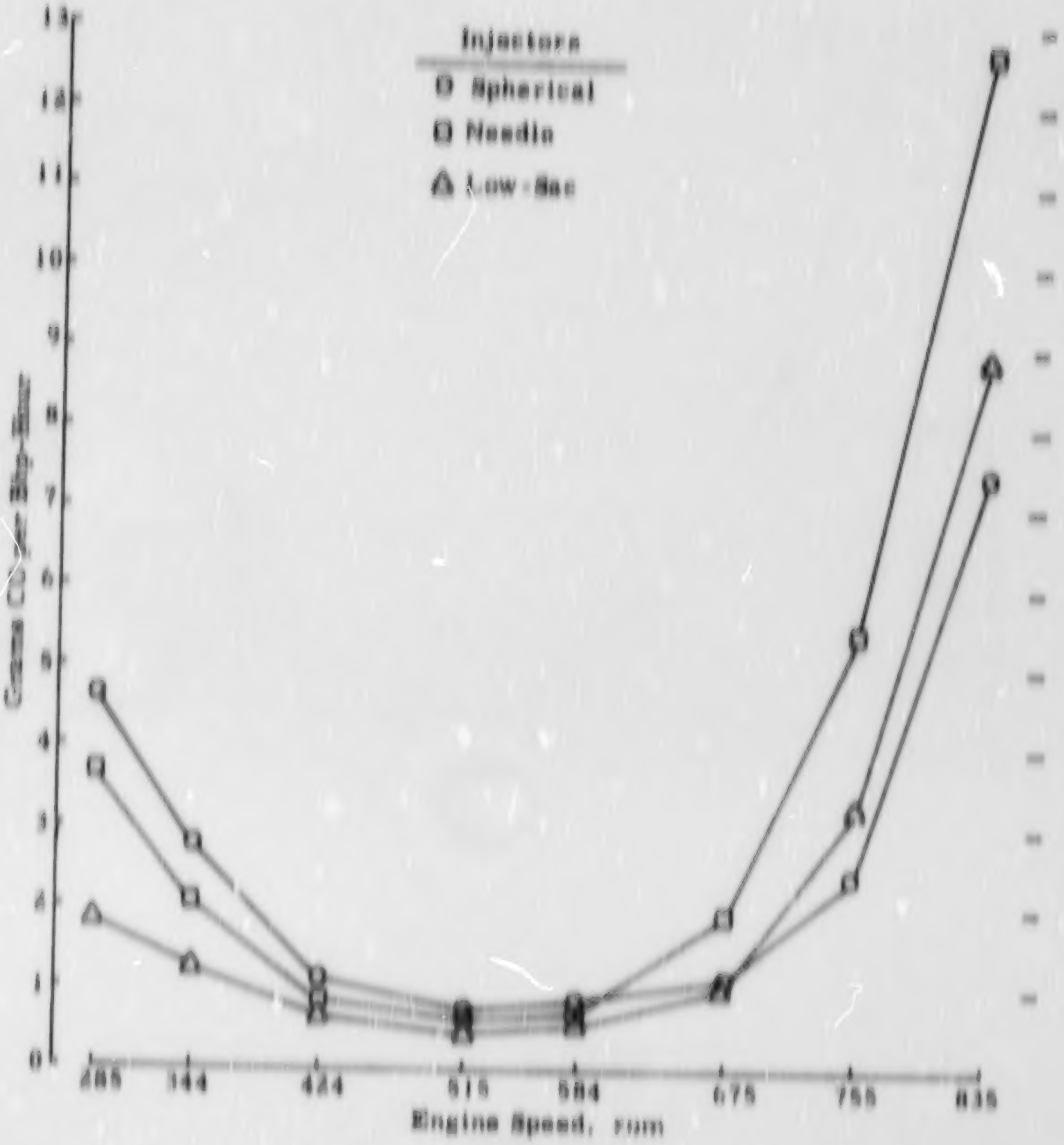

FIGURE C-4. MODAL BRAKE SPECIFIC CO FOR THREE TYPES OF FUEL INJECTORS AT STANDARD TIMING

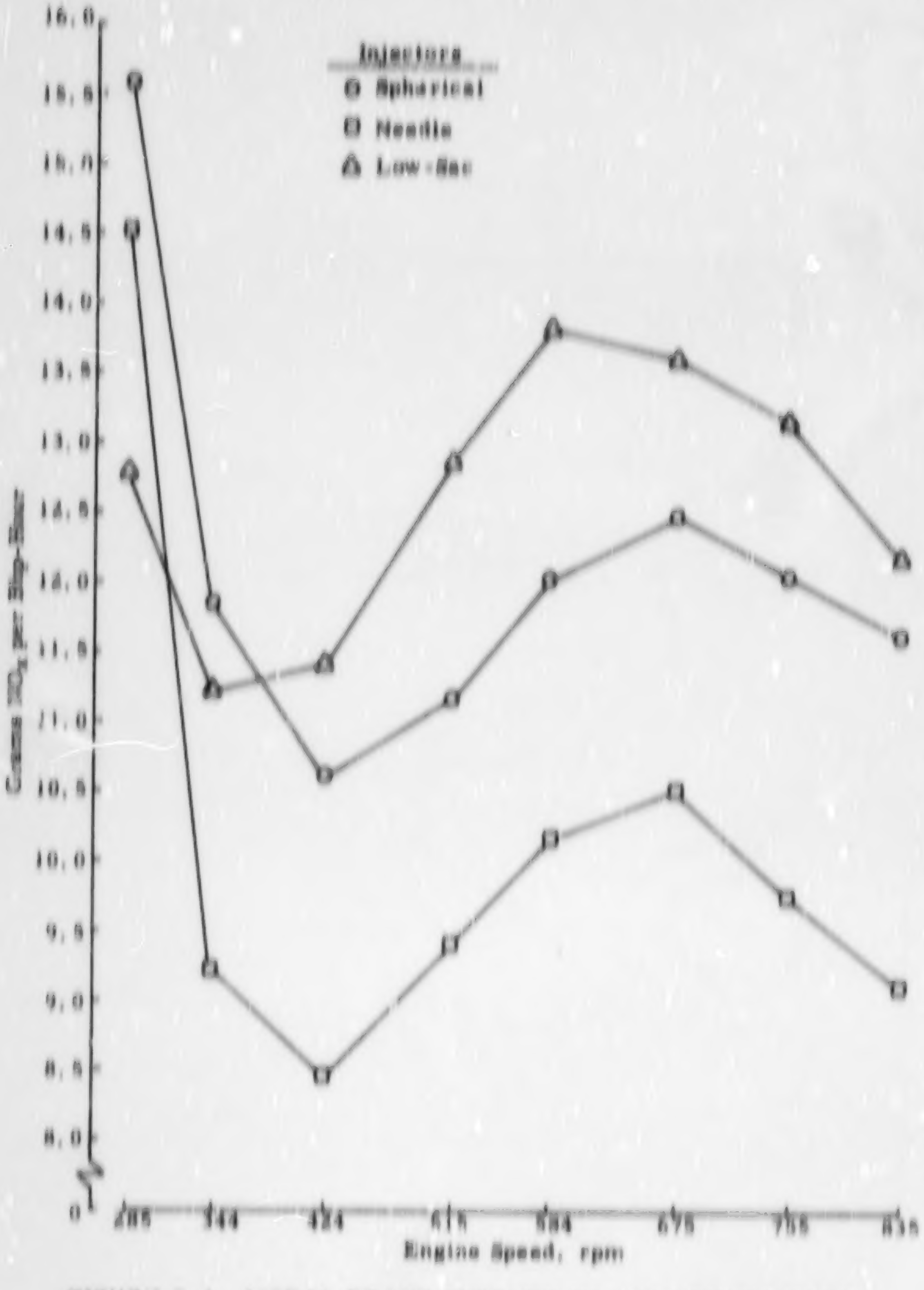

FIGURE C-1. MODAL BRAKE SPECIFIC NO_x FOR THREE TYPES OF FUEL INJECTORS AT STANDARD TIMING

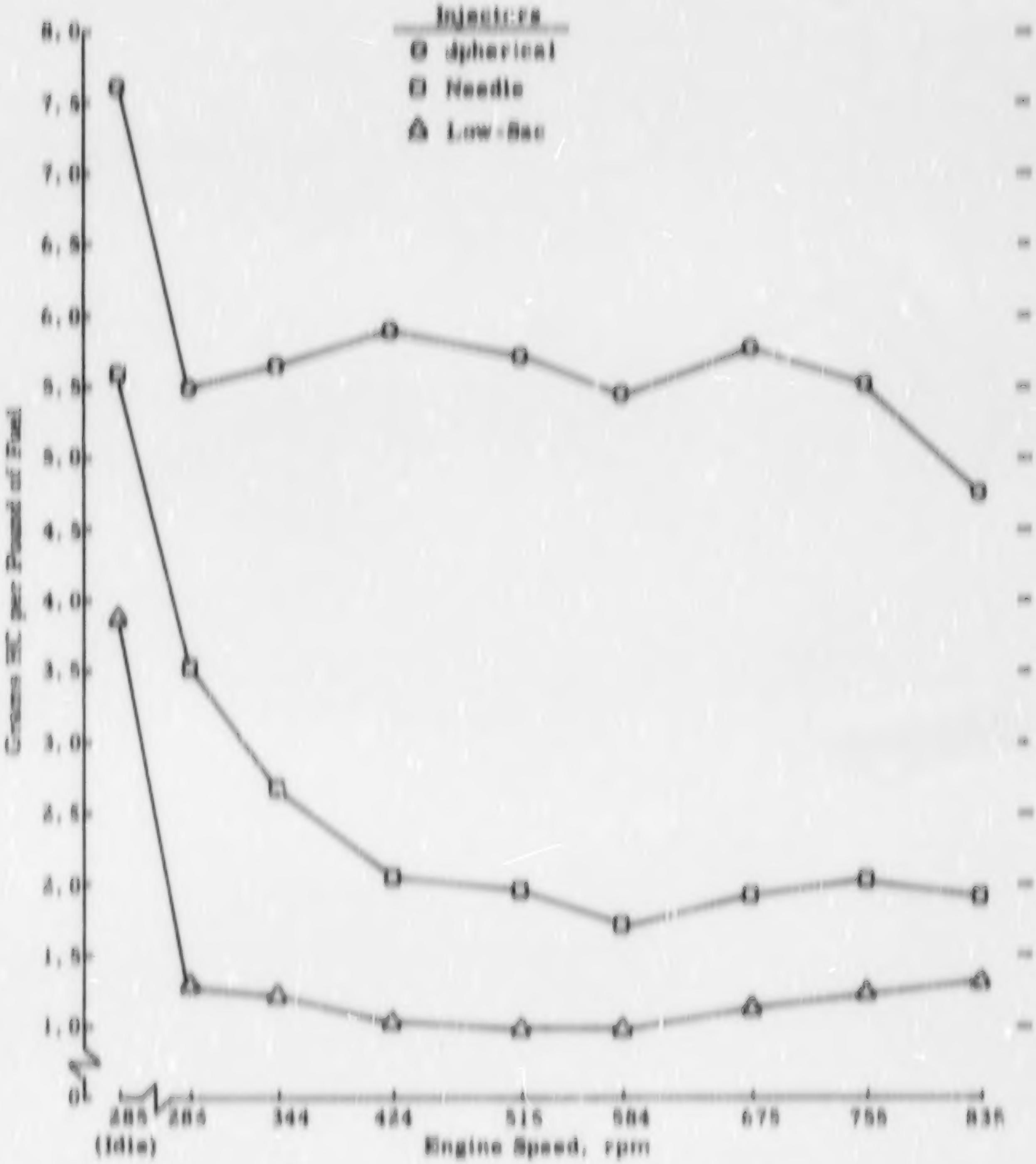

FIGURE C-4. MODAL FUEL SPECIFIC HC FOR THREE TYPES OF FUEL INJECTORS AT STANDARD TIMING

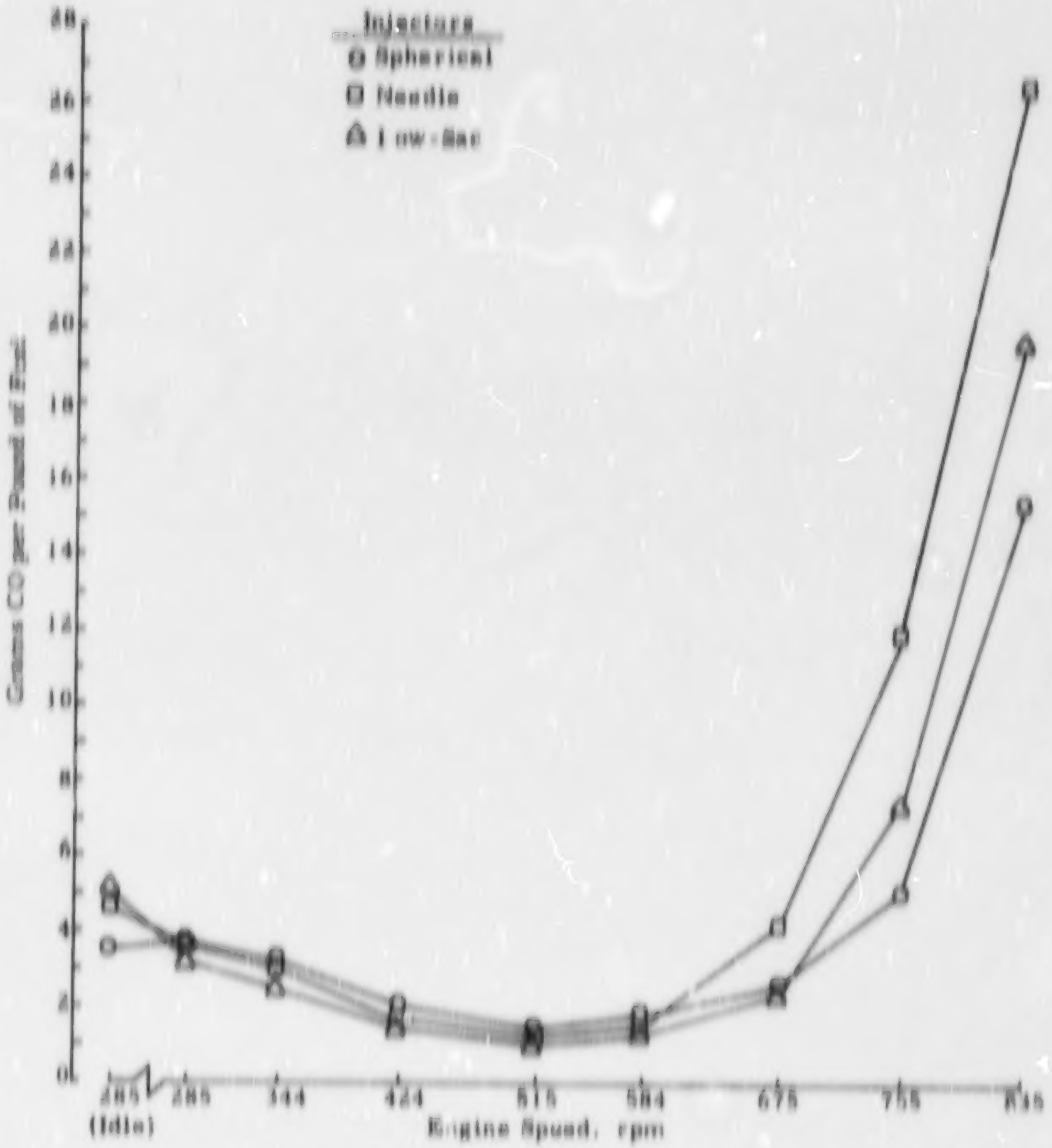

FIGURE C-5. MODAL FUEL SPECIFIC CO FOR THREE TYPES OF FUEL INJECTORS AT STANDARD TIMING

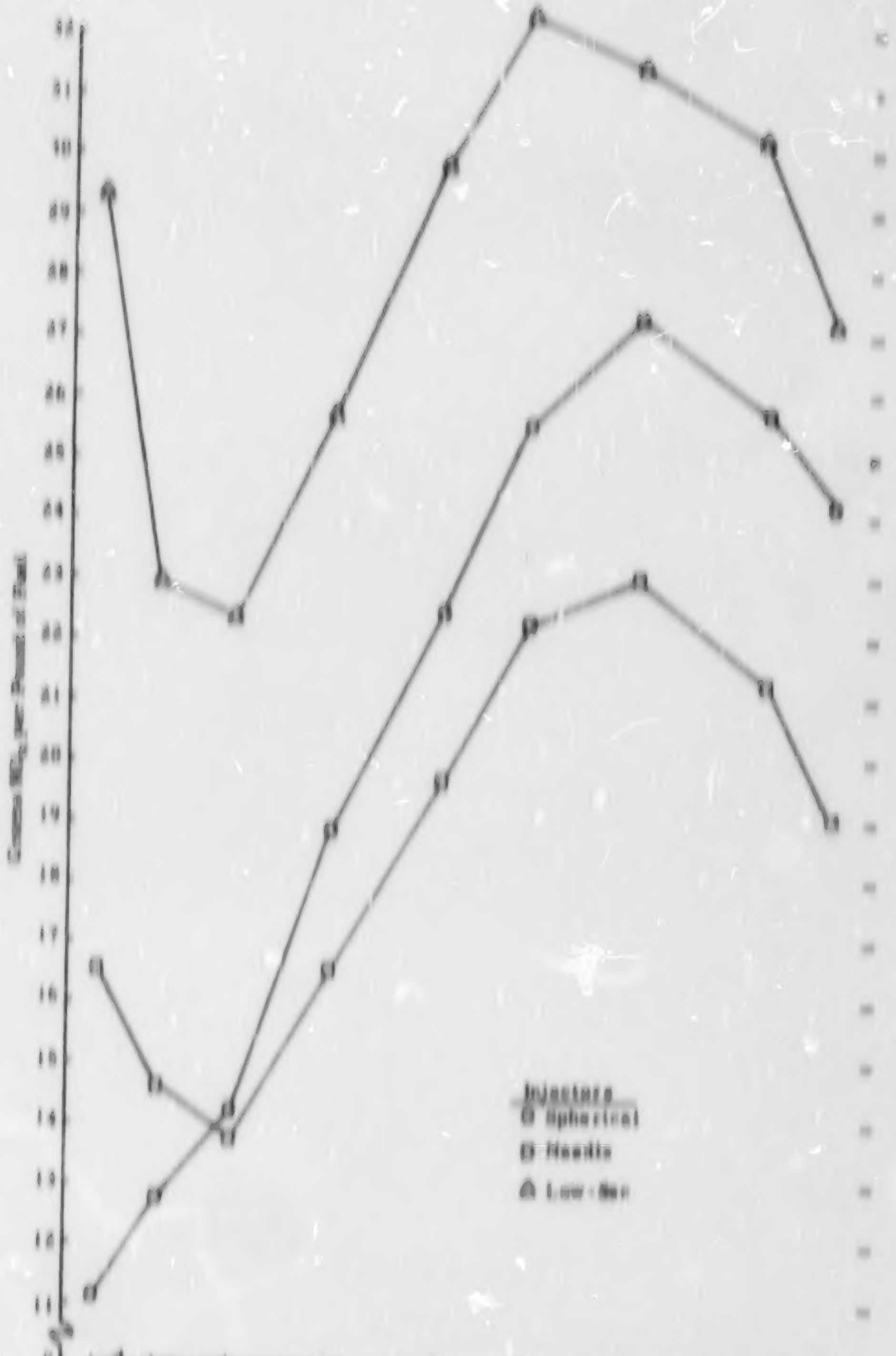

FIGURE C-5. MODAL FUEL SPECIFIC NO$_x$ FOR THREE TYPES OF FUEL INJECTORS AT STANDARD TIMING

TABLE C-2. MODAL BRAKE SPECIFIC AND FUEL SPECIFIC EMISSIONS FOR NEEDLE-VALVE INJECTORS AT ADVANCED AND RETARDED TIMING

Mode	Engine Speed, rpm	Grams/Bhp-Hour			Grams/Pound of Fuel		
		HC	CO	NO_x	HC	CO	NO_x
Standard Injection Timing (4° BTC)							
1, 6, 11	285	*	*	*	5.60	4.60	16.52
2	285	3.51	3.70	14.53	4.54	3.65	14.61
3	344	1.80	2.06	9.22	2.68	3.05	13.79
4	424	1.06	0.85	8.47	2.07	1.68	16.54
5	515	0.94	0.61	9.41	1.96	1.28	19.69
7	584	0.81	0.70	10.17	1.71	1.53	22.27
8	675	0.89	1.92	10.52	1.94	4.20	23.00
9	755	0.93	5.46	9.75	2.93	11.89	21.28
10	635	0.92	12.70	9.12	1.92	26.55	19.06
Injection 4° Advanced							
1, 6, 11	285	*	*	*	3.10	4.47	24.57
2	285	2.11	3.05	20.85	2.36	3.46	23.85
3	344	1.27	1.84	15.36	1.82	2.66	22.20
4	424	0.69	0.79	13.59	1.36	1.55	26.74
5	515	0.89	0.54	13.91	1.31	1.20	30.84
7	584	0.84	0.48	15.47	1.20	1.06	34.57
8	675	0.66	2.12	15.74	1.45	4.68	34.76
9	755	0.75	5.74	14.10	1.66	12.75	31.33
10	835	0.75	12.03	12.81	1.60	25.63	27.30
Injection 4° Retarded							
1, 6, 11	285	*	*	*	6.16	5.33	15.15
2	285	1.96	2.14	7.75	3.00	3.33	12.07
3	344	1.28	1.51	6.13	2.31	2.77	11.66
4	424	0.90	0.76	6.22	1.90	1.60	13.24
5	515	0.85	0.69	6.84	1.88	1.53	15.21
7	584	0.78	1.34	7.01	1.76	3.06	15.91
8	675	0.77	2.65	7.56	1.75	6.01	17.11
9	755	0.90	6.62	7.26	2.03	14.81	16.23
10	835	0.88	14.52	6.93	1.89	31.10	14.84

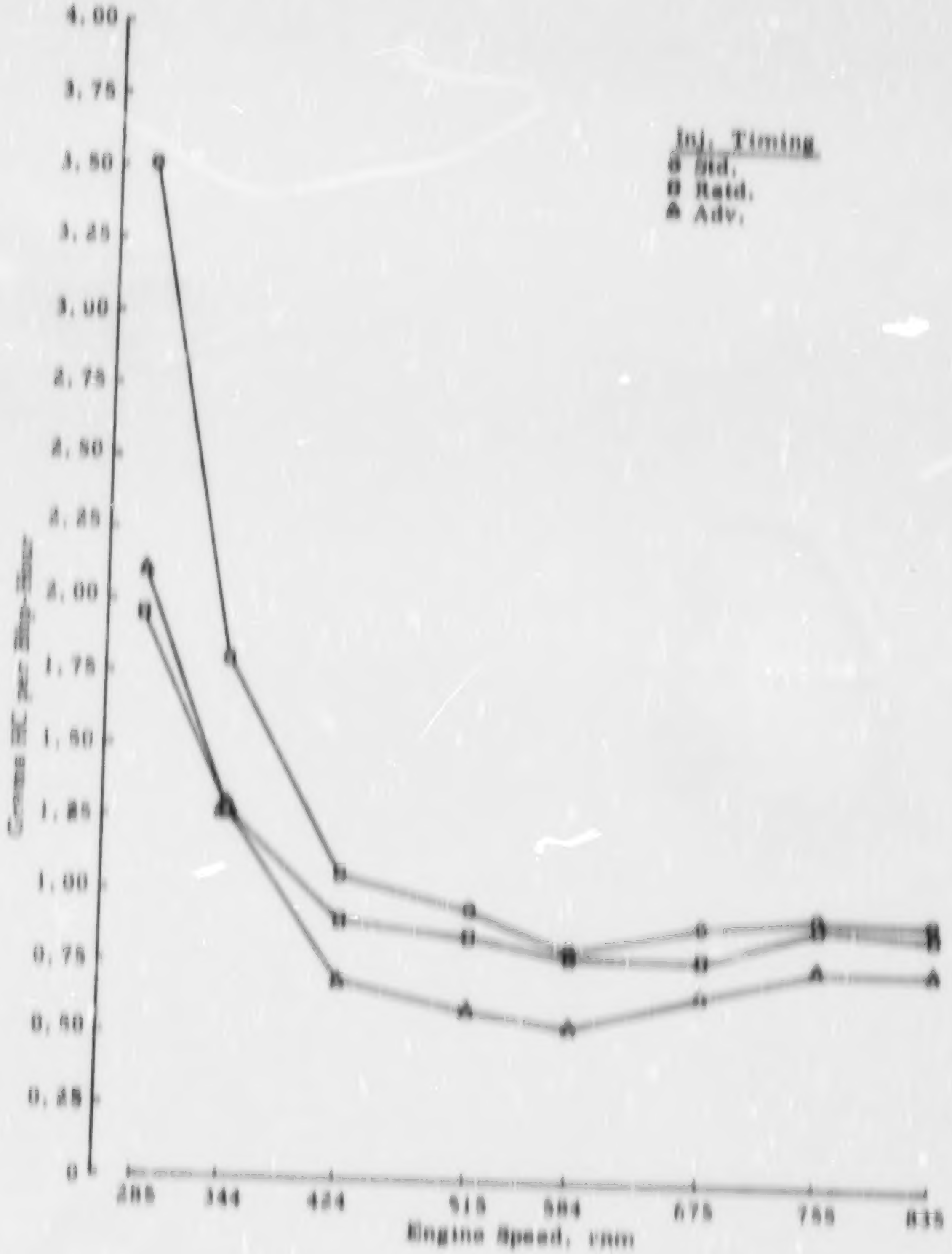

FIGURE C-7. MODAL BRAKE SPECIFIC HC FOR NEEDLE-VALVE INJECTORS AT THREE TIMING SETTINGS

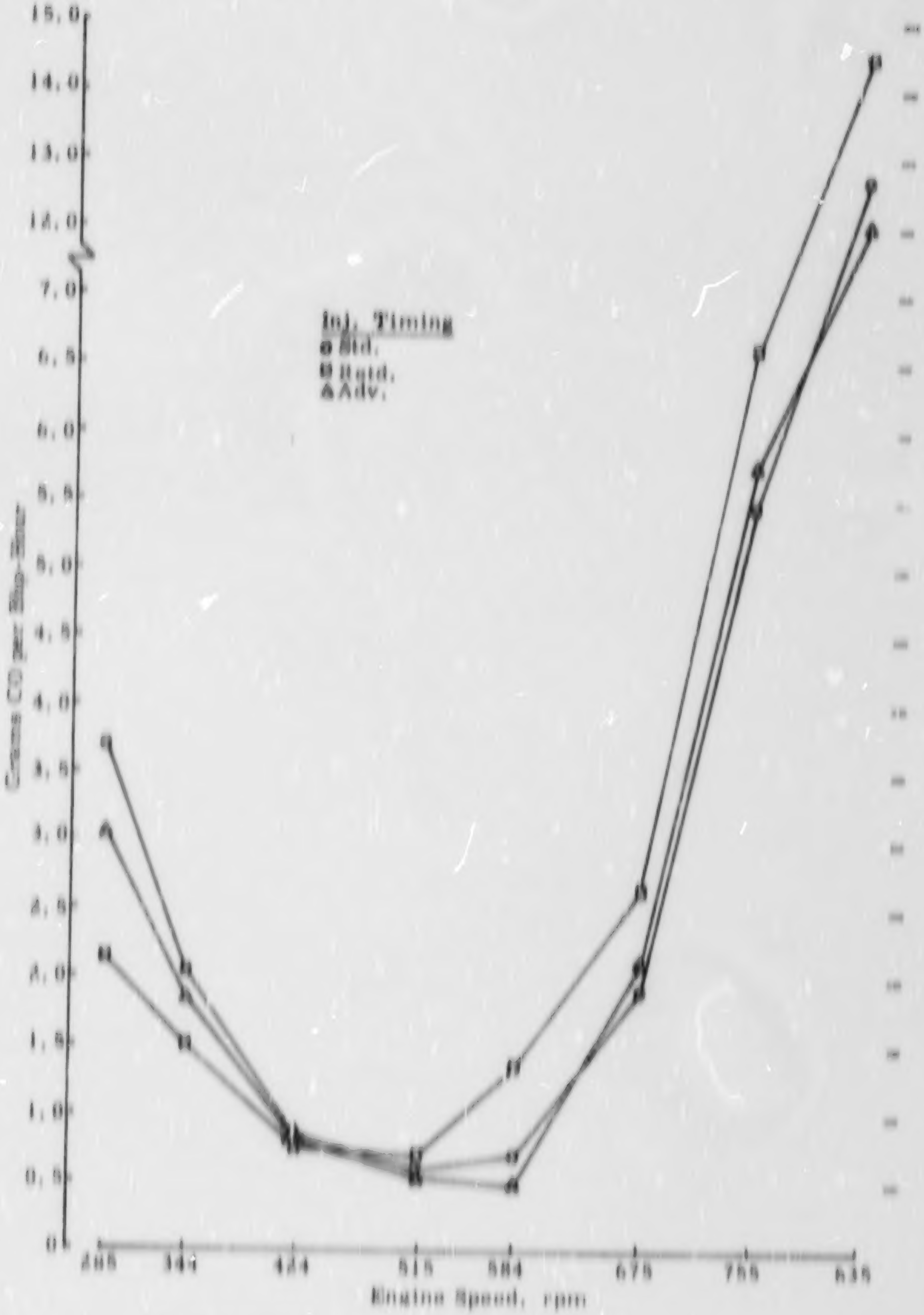

FIGURE C-8. MODAL BRAKE SPECIFIC CO FOR NEEDLE-VALVE INJECTORS AT THREE TIMING SETTINGS

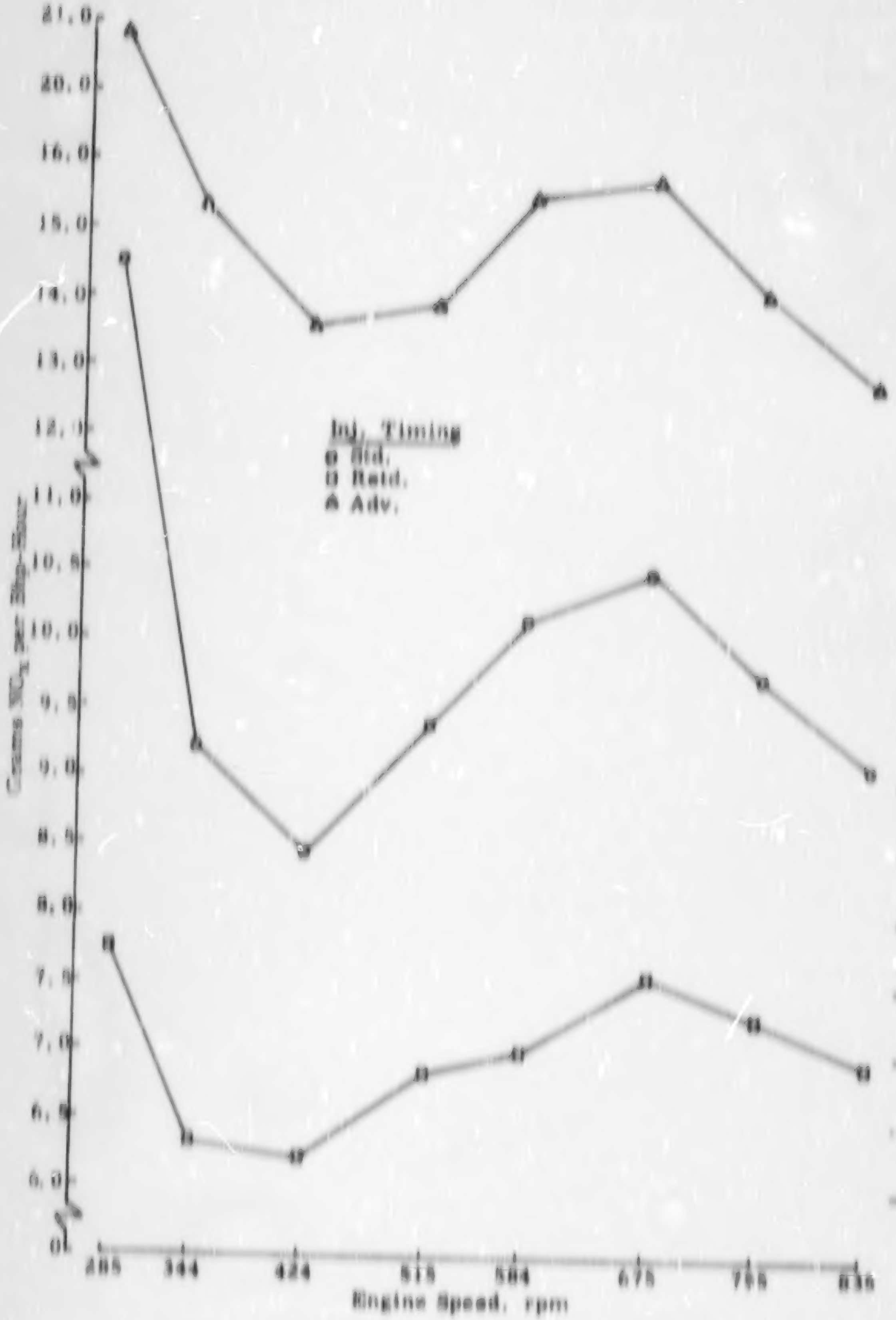

FIGURE C-9. MODAL BRAKE SPECIFIC NO_x FOR NEEDLE-VALVE INJECTORS AT THREE TIMING SETTINGS

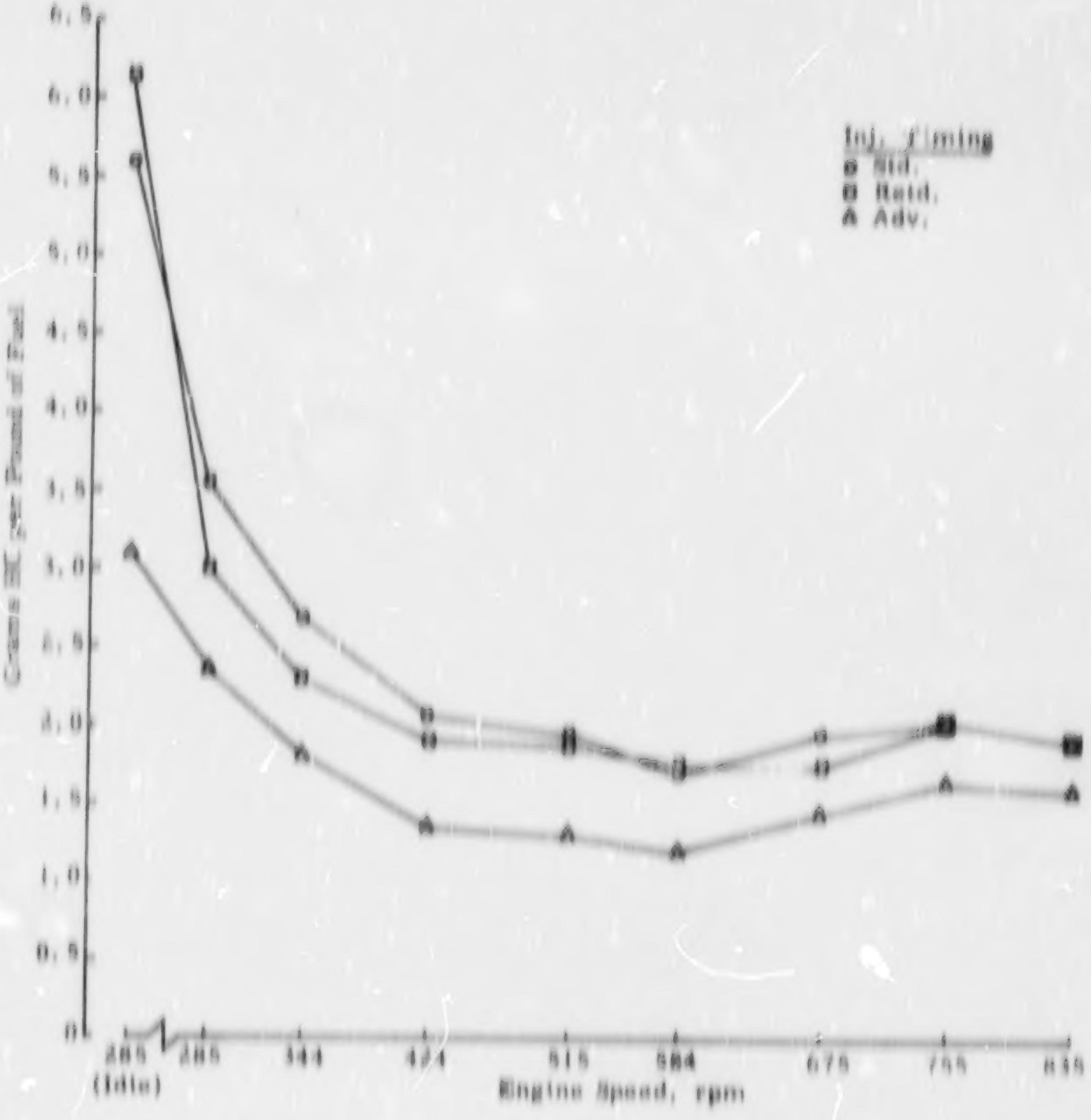

FIGURE C-10. MODAL FUEL SPECIFIC HC FOR NEEDLE-VALVE INJECTORS AT THREE TIMING SETTINGS

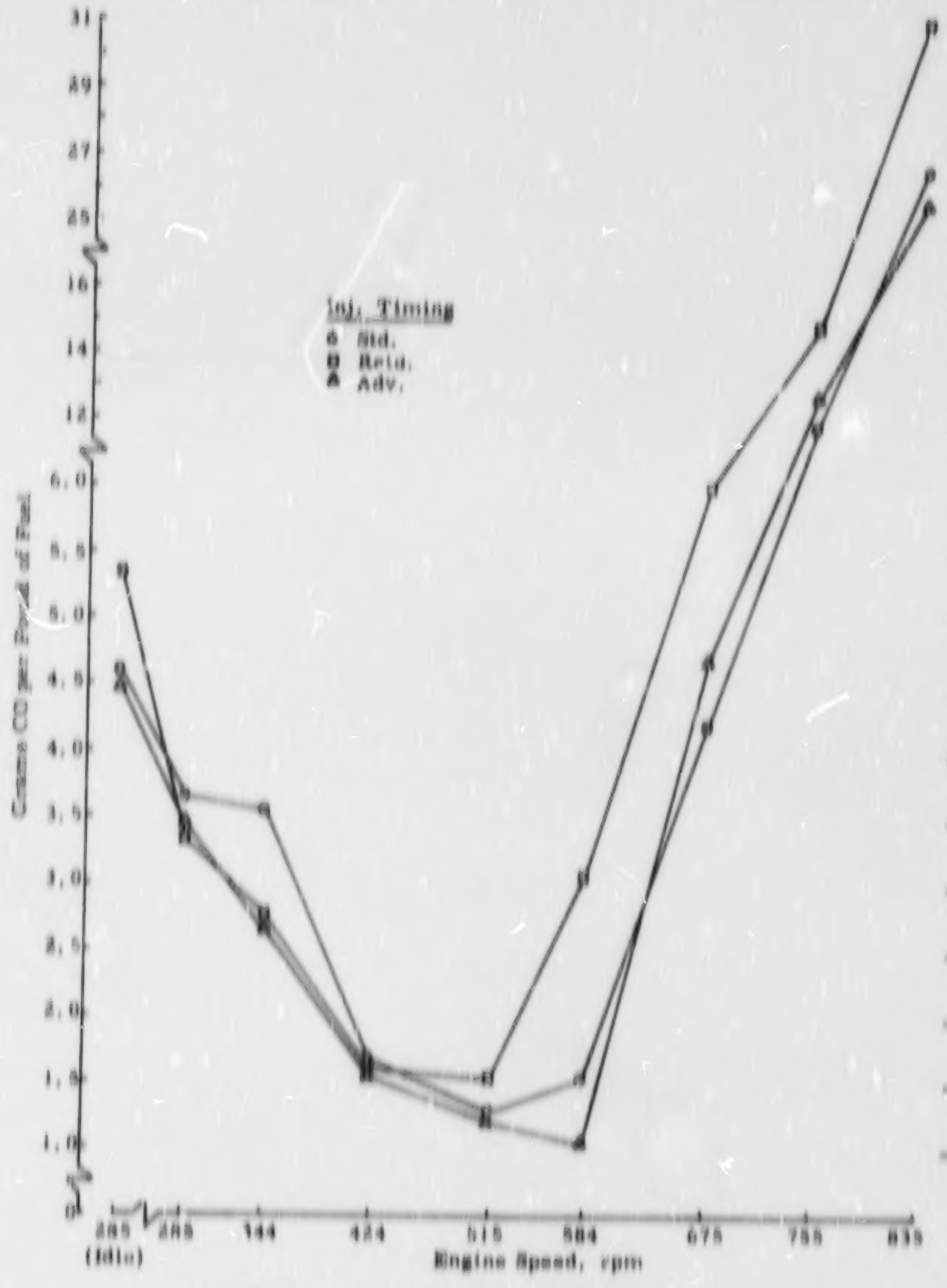

FIGURE C-11. MODAL FUEL SPECIFIC CO FOR NEEDLE-VALVE INJECTORS AT THREE TIMING SETTINGS

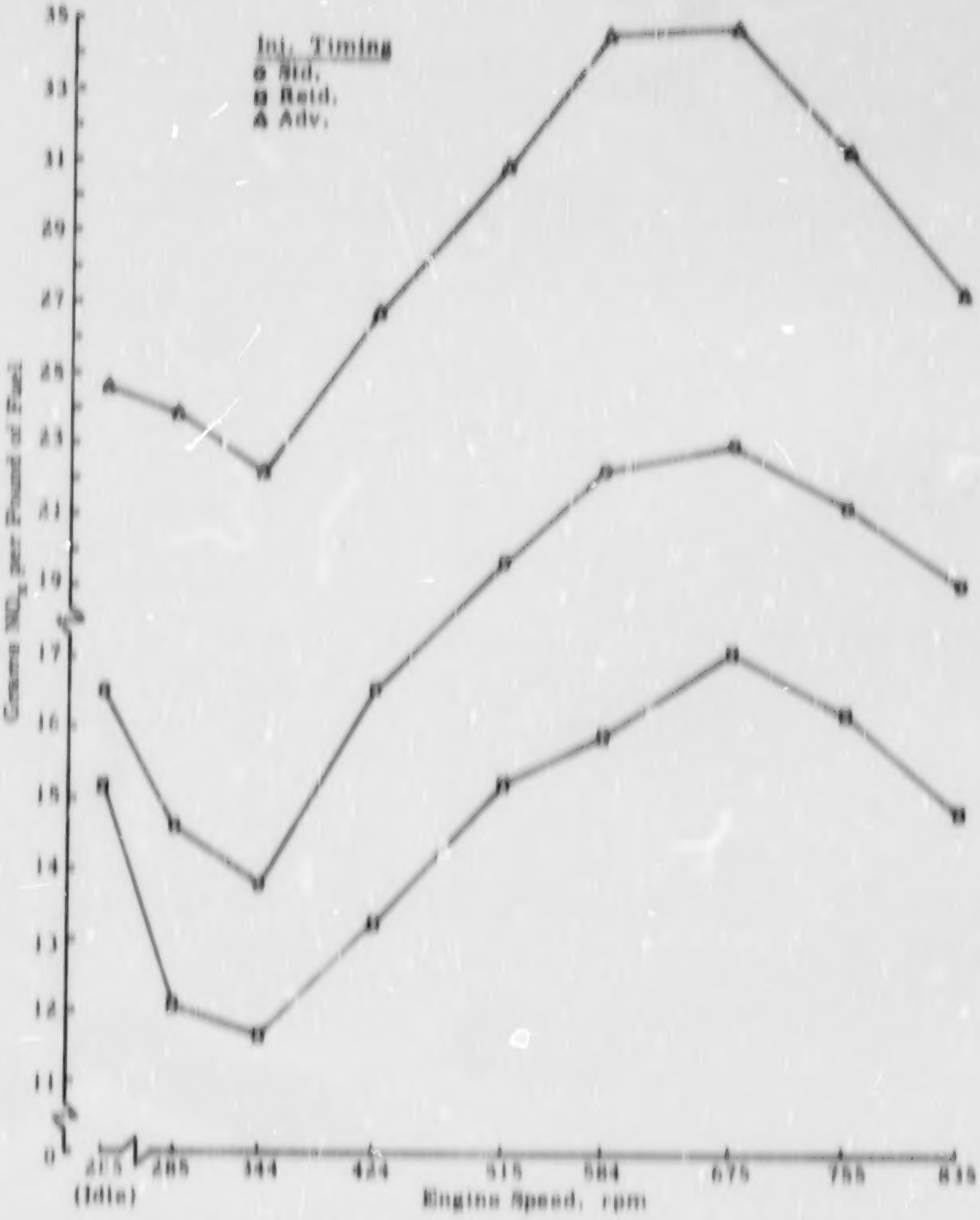

FIGURE C-12. MODAL FUEL SPECIFIC NO$_x$ FOR NEEDLE-VALVE INJECTORS AT THREE TIMING SETTINGS

TABLE C-7. MODAL BRAKE SPECIFIC AND FUEL SPECIFIC EMISSIONS FOR LOW-SAC INJECTORS AT RETARDED TIMING

Mode	Engine Speed, rpm	Grams/Bhp-Hour			Grams/Pound of Fuel		
		HC	CO	NO_x	HC	CO	NO_x
		Standard Injection Timing (4° BTC)					
1, 6, 11	285	*	*	*	3.86	5.08	29.33
2	285	0.71	1.81	12.79	1.28	3.24	22.92
3	344	0.61	1.25	11.23	1.22	2.49	22.39
4	424	0.46	0.69	11.41	1.03	1.55	25.72
5	515	0.43	0.44	12.87	0.99	1.03	29.84
7	584	0.42	0.56	13.82	0.99	1.31	32.30
8	675	0.49	1.04	13.61	1.14	2.41	31.47
9	755	0.54	3.28	13.16	1.24	7.56	30.27
10	835	0.60	8.86	12.19	1.32	19.75	27.20
		Injection 4° Retarded					
1, 6, 11	285	*	*	*	3.86	6.48	24.22
2	285	0.71	1.61	8.99	1.34	3.04	16.81
3	344	0.61	1.34	8.00	1.22	2.69	16.04
4	424	0.44	0.68	7.90	1.01	1.54	17.82
5	515	0.41	0.55	9.36	0.97	1.30	22.03
7	584	0.39	1.05	9.84	0.90	2.43	22.84
8	675	0.45	1.99	9.68	1.03	4.60	22.32
9	755	0.49	5.01	9.27	1.13	11.45	21.20
10	835	0.55	11.84	8.76	1.21	26.20	19.36

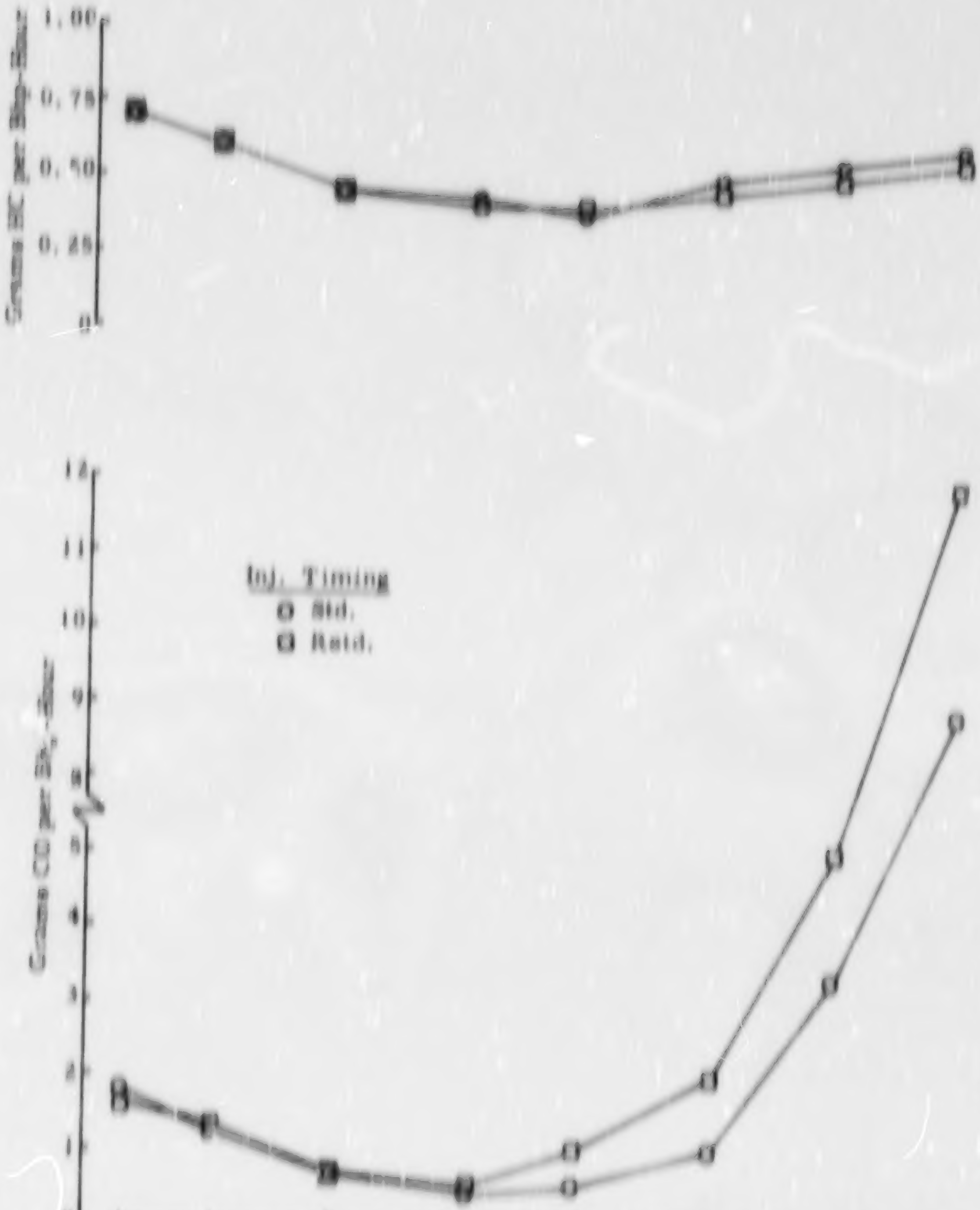

FIGURE C-13. MODAL BRAKE SPECIFIC HC AND CO FOR LOW-SAC INJECTORS AT STANDARD AND RETARDED TIMING

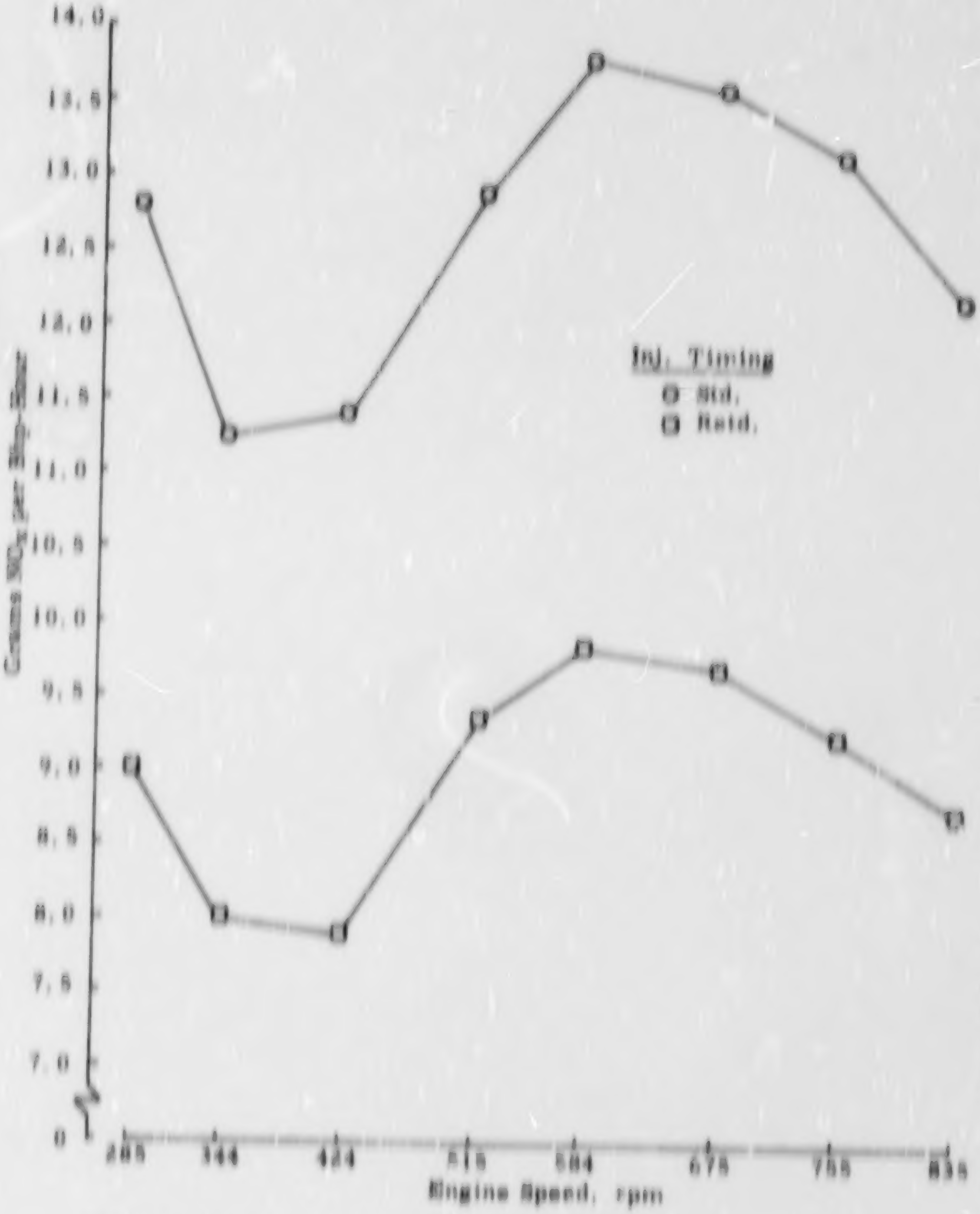

FIGURE C-14. MODAL BRAKE SPECIFIC NO_x FOR LOW-SAC INJECTORS AT STANDARD AND RETARDED TIMING

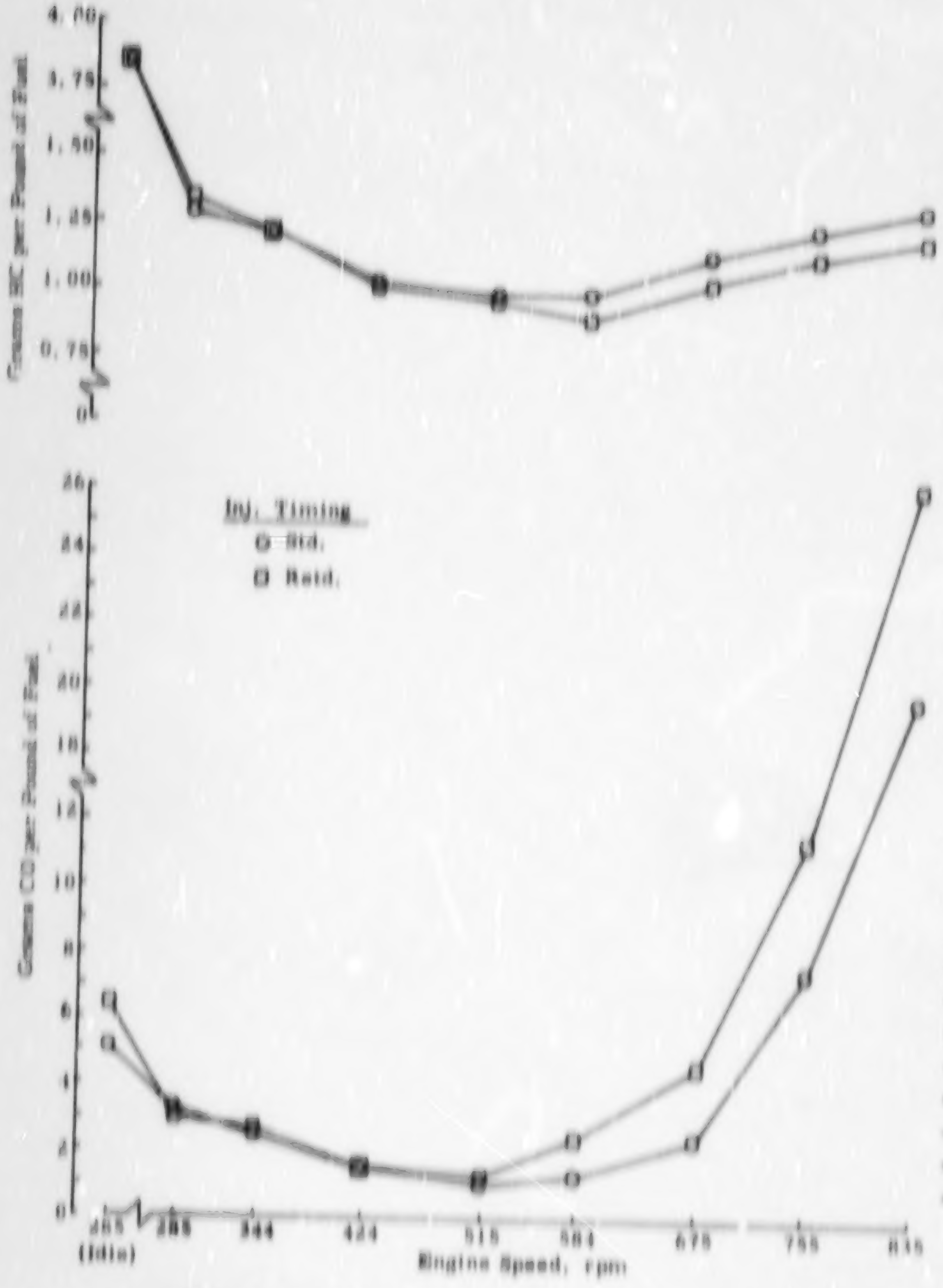

FIGURE C-15. MODAL FUEL SPECIFIC HC AND CO FOR LOW-SAC INJECTORS AT STANDARD AND RETARDED TIMING

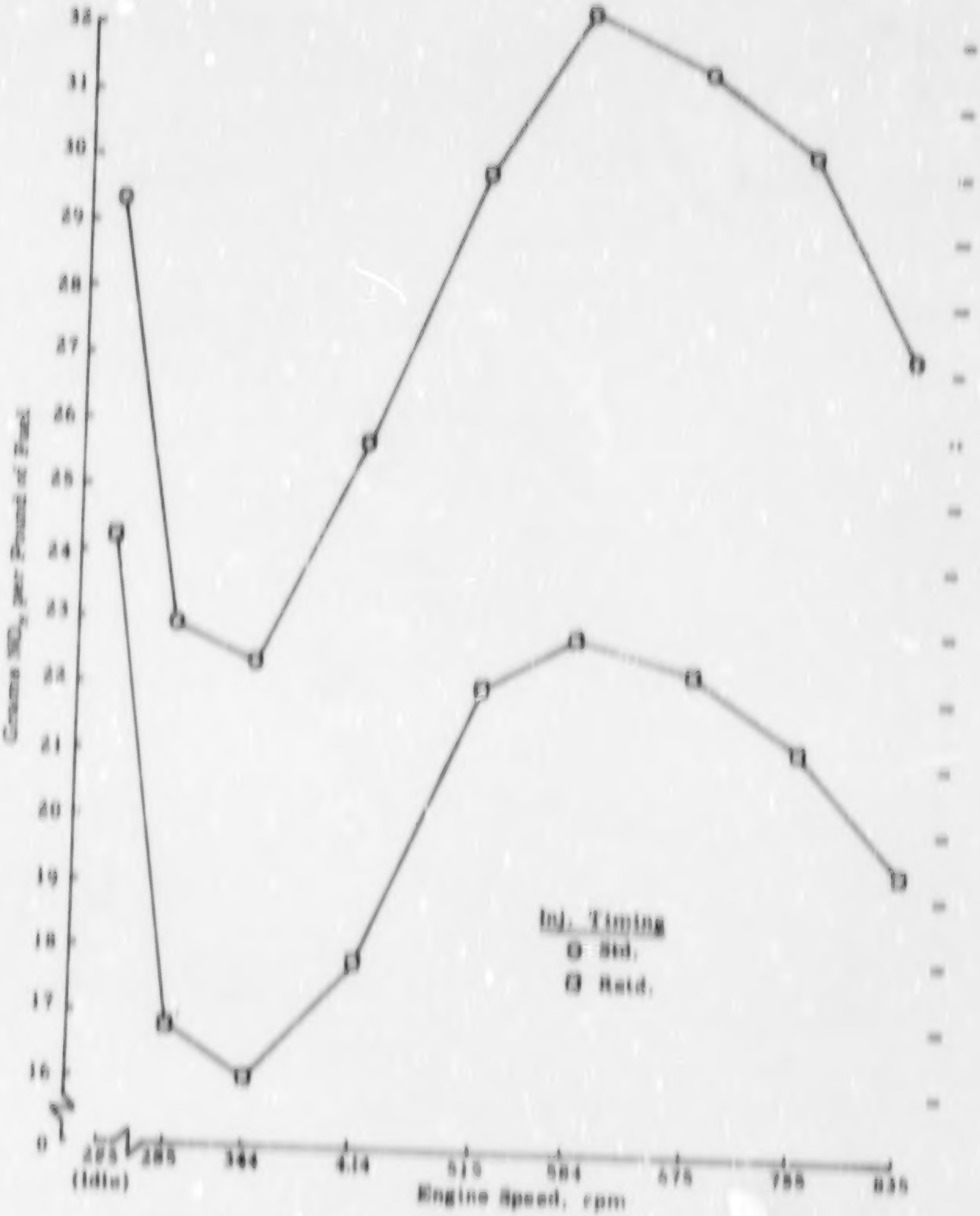

FIGURE C-16. MODAL FUEL SPECIFIC NO_x FOR LOW-SAC INJECTORS AT STANDARD AND RETARDED TIMING

TABLE C-4. MODAL BRAKE SPECIFIC AND FUEL SPECIFIC EMISSIONS FOR NEEDLE-VALVE INJECTORS, STANDARD TIMING, AND WATER INDUCTION

Mode	Engine Speed, rpm	Grams/Bhp-Hour			Grams/Pound of Fuel		
		HC	CO	NO_x	HC	CO	NO_x
		0% Water Induction*					
1,6,11	285	-	-	-	5,60	4,60	16,52
2	285	3,51	3,70	14,53	3,54	3,65	14,61
3	344	1,80	2,06	9,22	2,68	3,05	13,79
4	424	1,06	0,85	8,47	2,07	1,68	16,54
5	515	0,94	0,61	9,41	1,96	1,28	19,69
7	584	0,81	0,70	10,17	1,71	1,53	22,27
8	675	0,89	1,92	10,52	1,94	4,20	23,00
9	755	0,93	5,46	9,75	2,03	11,89	21,28
10	835	0,92	12,70	9,12	1,92	26,55	19,06
		25% Water Induction*					
1,6,11	285	-	-	-	5,39	5,19	23,31
2	285	1,34	1,79	10,18	2,37	3,18	18,05
3	344	0,98	1,36	8,51	1,95	2,71	16,99
4	424	0,70	0,68	8,34	1,59	1,53	18,89
5	515	0,66	0,48	9,25	1,54	1,13	21,68
7	584	0,66	0,80	10,27	1,47	1,76	22,70
8	675	0,68	1,91	9,78	1,59	4,48	22,96
9	755	0,81	5,30	9,15	1,86	12,12	20,94
10	835	0,79	12,44	8,43	1,72	27,33	18,52
		50% Water Induction*					
1,6,11	285	-	-	-	5,34	6,56	24,45
2	285	1,29	2,04	9,44	2,55	4,04	18,65
3	344	0,87	1,47	7,50	1,85	3,16	16,01
4	424	0,59	0,74	7,60	1,39	1,75	17,88
5	515	0,57	0,64	8,17	1,38	1,54	19,57
7	584	0,59	0,97	8,79	1,42	2,34	21,17
8	675	0,63	1,91	8,88	1,50	4,56	21,25
9	755	0,74	5,44	8,43	1,75	12,77	19,79
10	835	0,76	12,45	7,75	1,70	27,95	17,41

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*Percent of fuel flow mass per mode.

TABLE C-4. MODAL BRAKE SPECIFIC AND FUEL SPECIFIC EMISSIONS FOR NEEDLE-VALVE INJECTORS, STANDARD TIMING, AND WATER INDUCTION (Cont'd)

Mode	Engine Speed, rpm	Grams/Bhp-Hour			Grams/Pound of Fuel		
		HC	CO	NO_x	HC	CO	NO_x
		75% Water Induction*					
1, 6, 11	285	*	*	*	4.05	10.03	23.55
2	285	0.87	2.28	8.15	1.85	4.81	17.67
3	344	0.70	1.78	7.26	1.51	3.83	15.58
4	424	0.50	1.04	7.03	1.18	2.47	16.63
5	515	0.47	0.96	8.88	1.12	2.29	21.23
7	584	0.51	1.30	8.39	1.23	3.14	20.19
8	675	0.56	2.32	8.36	1.35	5.58	20.14
9	755	0.65	5.57	7.87	1.54	13.24	17.98
10	835	0.68	12.21	6.88	1.54	27.50	15.51
		100% Water Induction*					
1, 6, 11	285	*	*	*	5.19	5.29	21.24
2	285	1.22	1.02	9.19	2.13	1.81	16.18
3	344	1.05	0.98	8.11	2.03	2.26	16.02
4	424	0.70	0.51	8.09	1.53	1.11	17.69
5	515	0.69	0.41	8.65	1.55	0.93	19.61
7	584	0.66	0.87	9.60	1.46	1.93	21.43
8	675	0.70	2.34	9.04	1.59	5.31	20.53
9	755	0.77	6.19	8.21	1.73	13.87	18.40
10	835	0.81	13.76	7.07	1.76	29.80	15.28

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*Percent of fuel flow mass per mode.

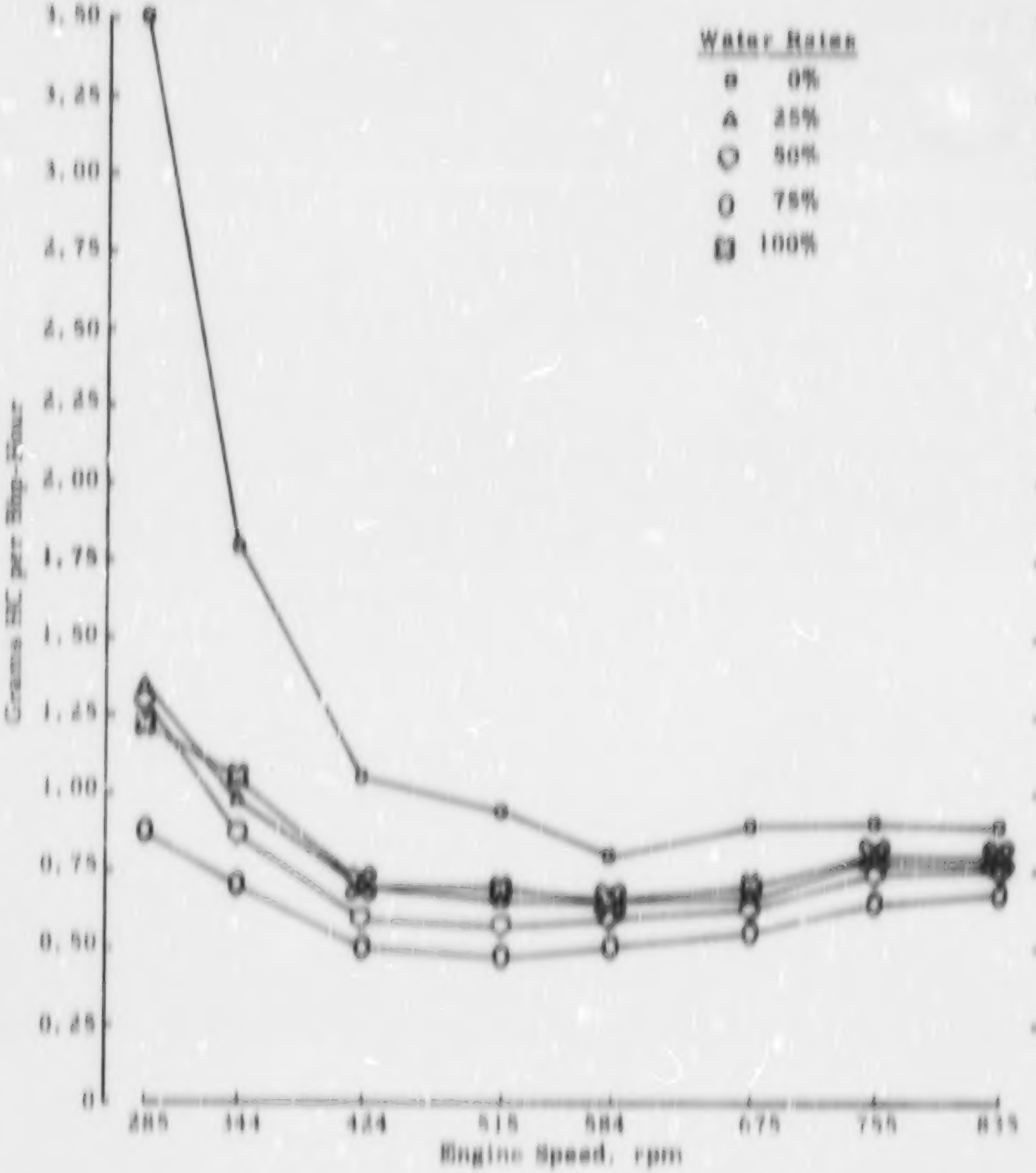

FIGURE C-17. MODAL BRAKE SPECIFIC HC FOR VARIOUS WATER INDUCTION RATES--NEEDLE-VALVE INJECTORS AT STANDARD TIMING

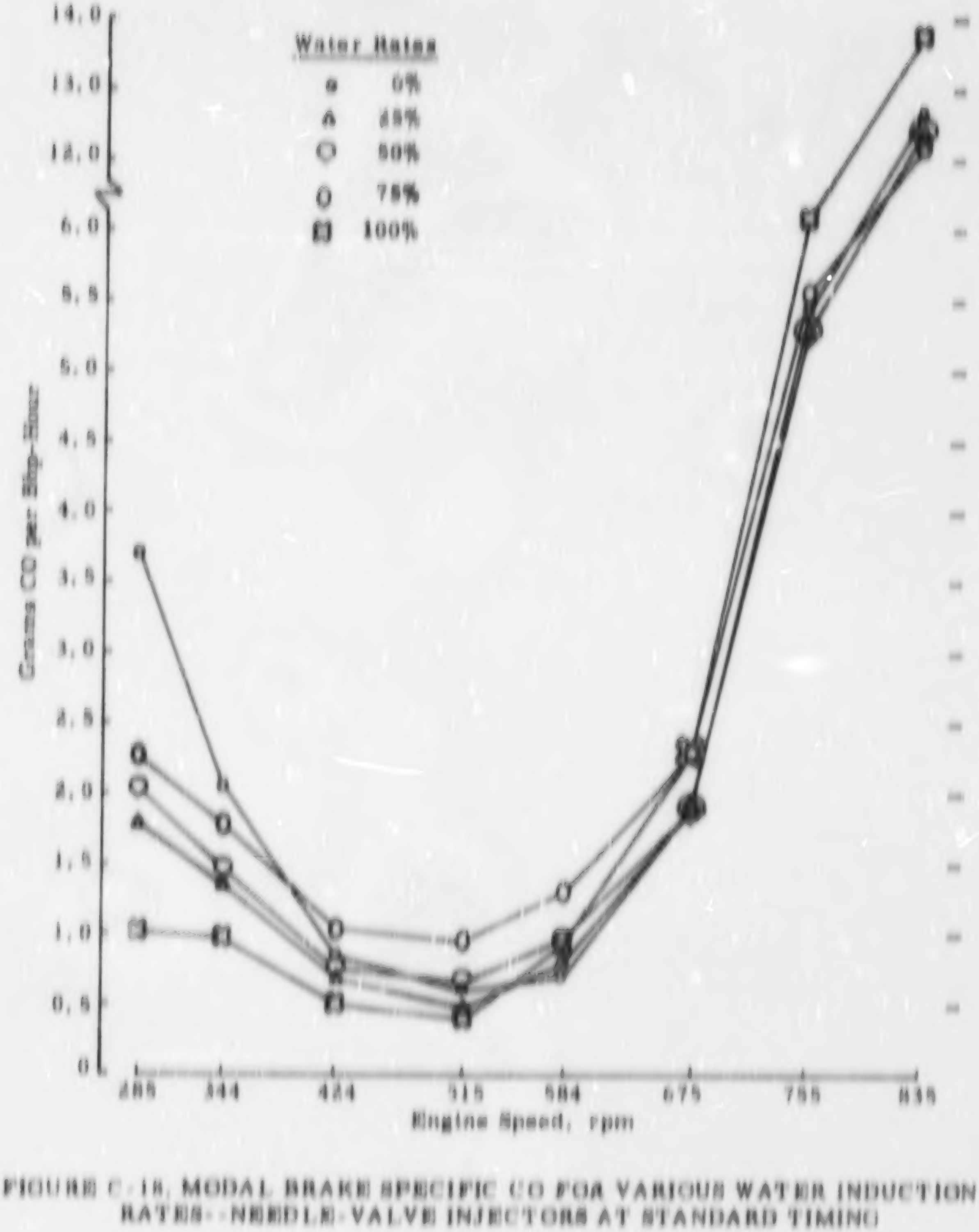

FIGURE C-18. MODAL BRAKE SPECIFIC CO FOR VARIOUS WATER INDUCTION RATES--NEEDLE-VALVE INJECTORS AT STANDARD TIMING

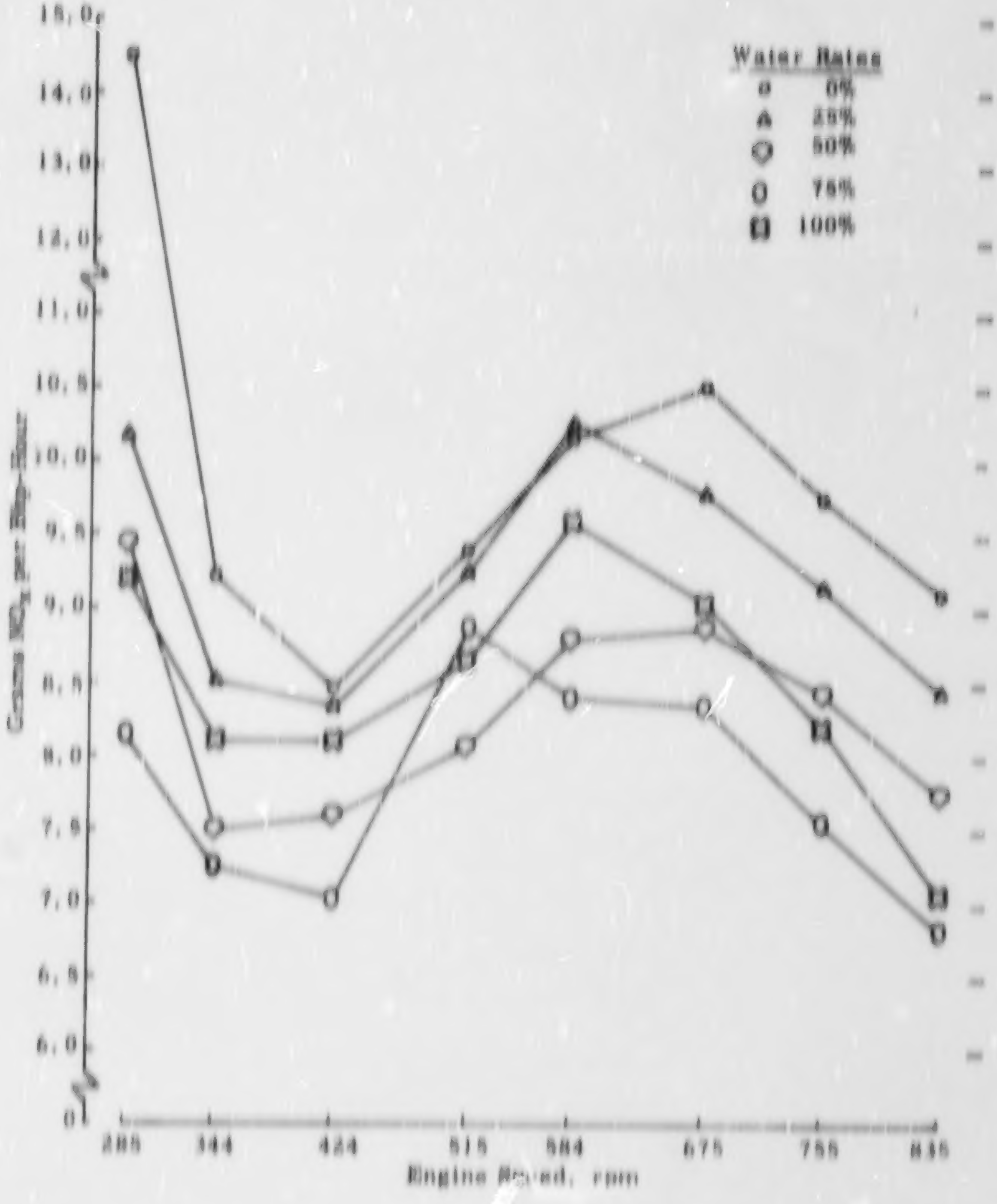

FIGURE C-19. MODAL BRAKE SPECIFIC NO$_x$ FOR VARIOUS WATER INDUCTION RATES--NEEDLE-VALVE INJECTORS AT STANDARD TIMING

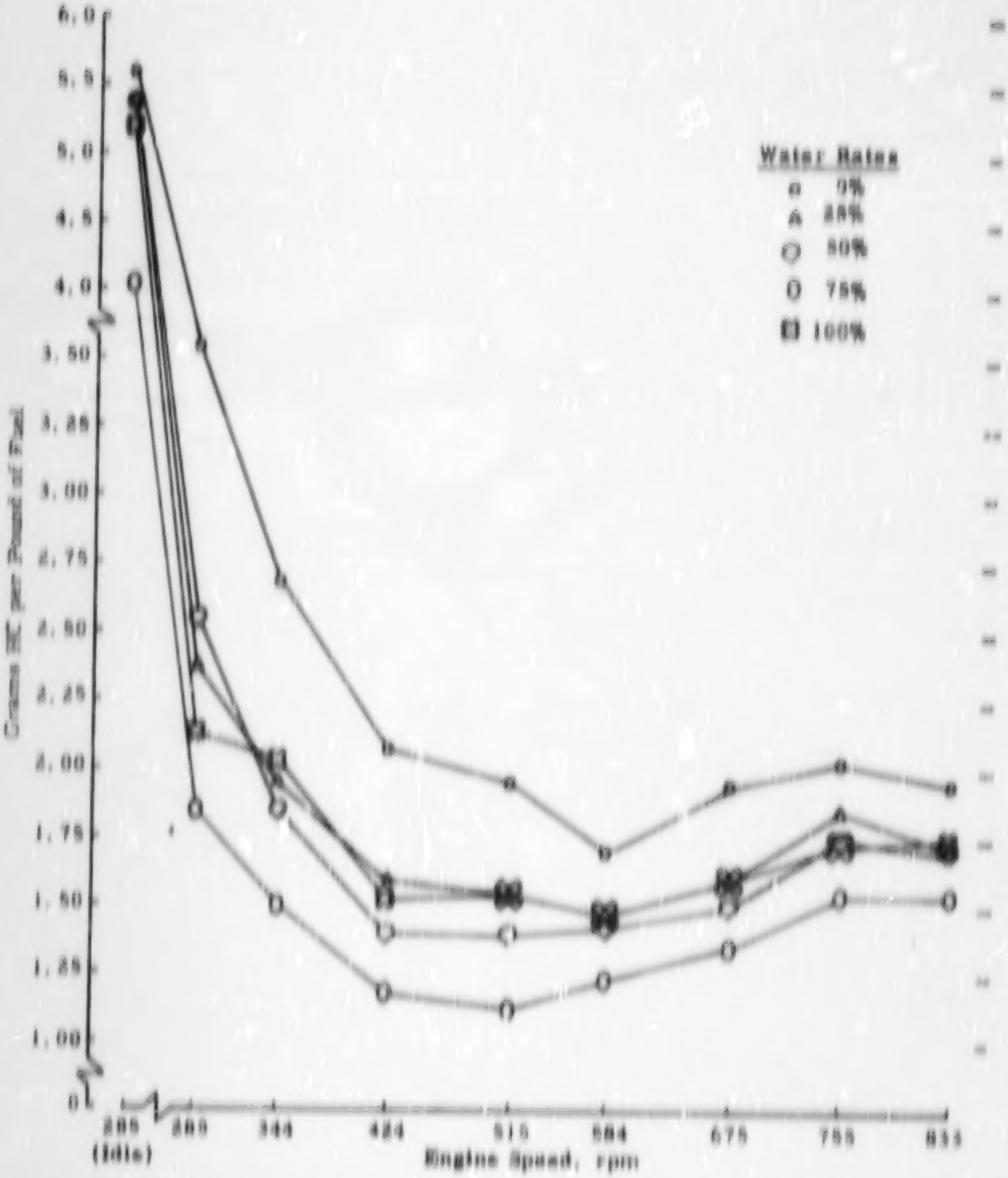

FIGURE C-20. MODAL FUEL SPECIFIC HC FOR VARIOUS WATER INDUCTION RATES--NEEDLE-VALVE INJECTORS AT STANDARD TIMING

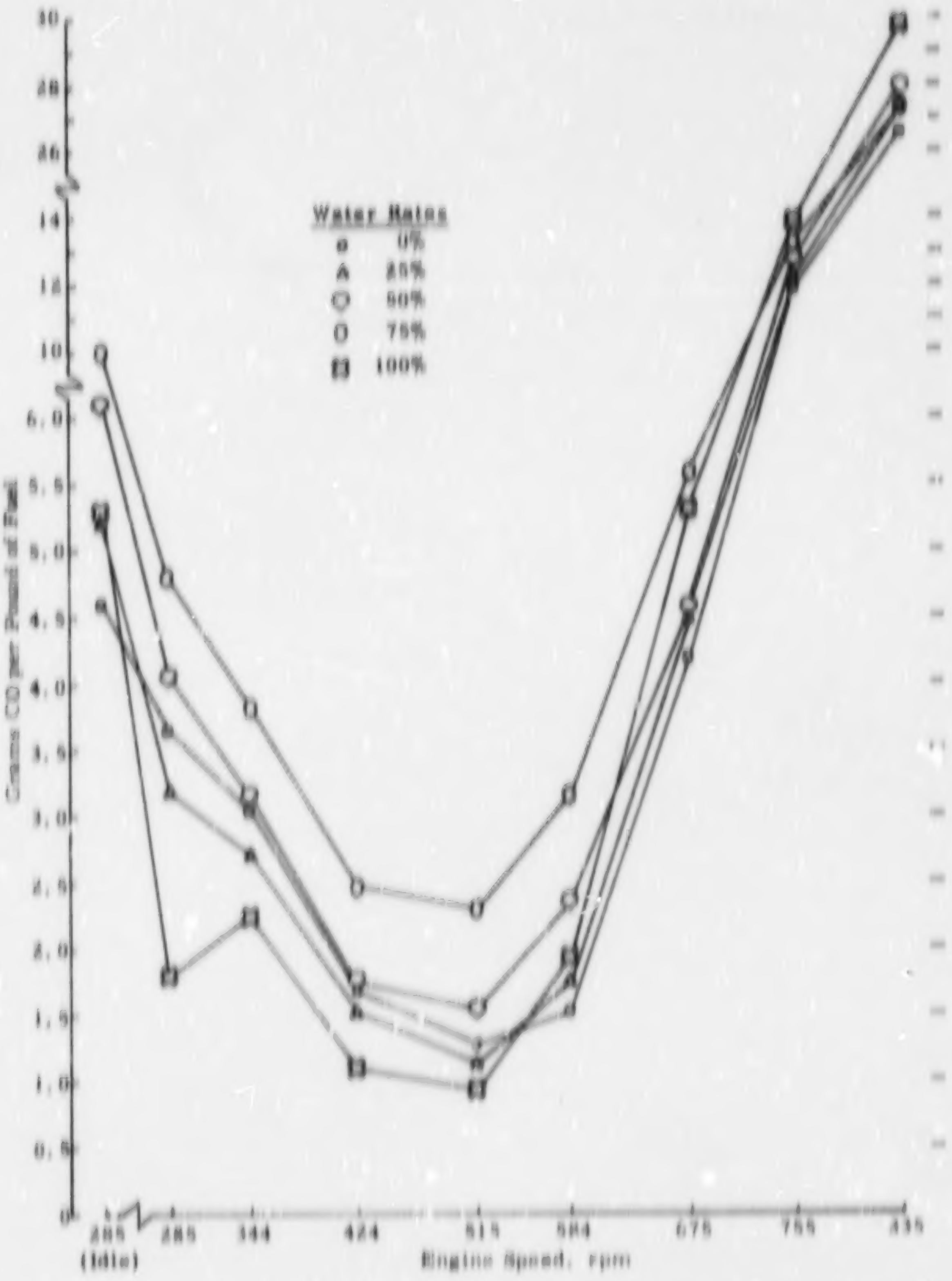

FIGURE C-31. MODAL FUEL SPECIFIC CO FOR VARIOUS WATER INDUCTION RATES--NEEDLE-VALVE INJECTORS AT STANDARD TIMING

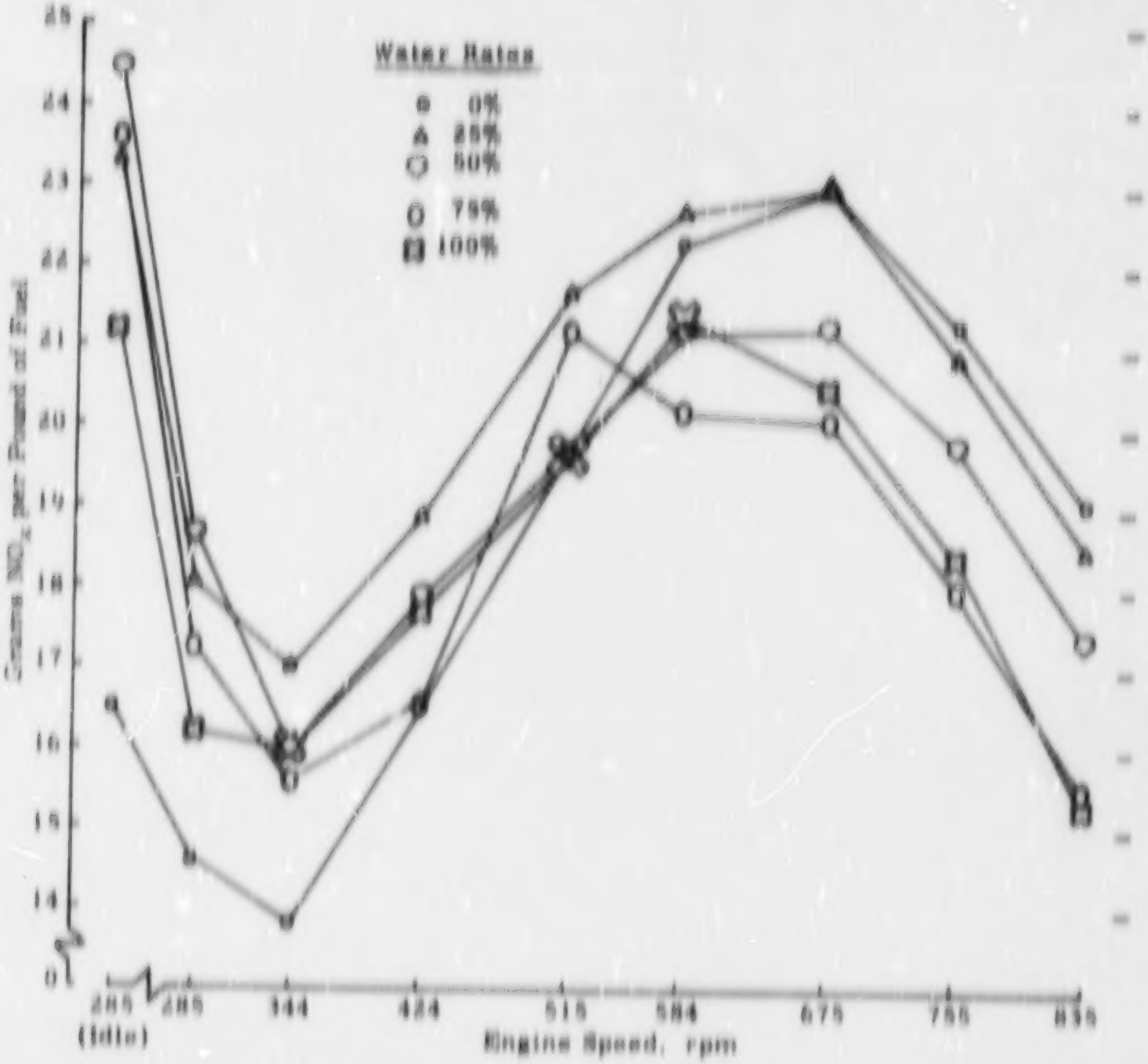

FIGURE C-22. MODAL FUEL SPECIFIC NO_x FOR VARIOUS WATER INDUCTION RATES--NEEDLE-VALVE INJECTORS AT STANDARD TIMING

TABLE C-5. MODAL BRAKE SPECIFIC AND FUEL SPECIFIC EMISSIONS FOR LOW-SAC INJECTORS, STANDARD TIMING, AND WATER INDUCTION

Mode	Notch Position	Engine Speed, rpm	Grams/Bhp-Hour HC	Grams/Bhp-Hour CO	Grams/Bhp-Hour NO_x	Grams/Pound of Fuel HC	Grams/Pound of Fuel CO	Grams/Pound of Fuel NO_x
	0% Water Induction*							
1,6,11	Low Idle	285	*	*	*	3.86	5.08	29.33
2	1	285	0.71	1.81	12.79	1.28	3.24	22.92
3	2	344	0.61	1.25	11.23	1.22	2.49	22.39
4	3	424	0.46	0.69	11.41	1.03	1.55	25.72
5	4	515	0.43	0.44	12.87	0.99	1.03	29.84
7	5	584	0.42	0.56	13.82	0.99	1.31	32.30
8	6	675	0.49	1.04	13.61	1.14	2.41	31.47
9	7	755	0.54	3.28	13.16	1.24	7.56	30.27
10	8	835	0.60	8.86	12.19	1.32	19.75	27.20
	25% Water Induction*							
1,6,11	Low Idle	285	*	*	*	3.45	4.23	29.11
2	1	285	0.59	1.47	11.22	1.22	3.02	23.38
3	2	344	0.51	1.03	10.49	1.06	2.13	21.63
4	3	424	0.39	0.43	10.80	0.88	0.99	24.70
5	4	515	0.38	0.36	12.38	0.89	0.83	28.98
7	5	584	0.36	0.53	12.85	0.85	1.24	30.35
8	6	675	0.47	1.22	14.14	0.96	2.52	29.58
9	7	755	0.43	2.00	11.73	1.02	4.71	27.44
10	8	835	0.51	9.63	10.05	1.16	21.75	24.94
	50% Water Induction*							
1,6,11	Low Idle	285	*	*	*	3.88	4.79	28.77
2	1	285	0.61	1.68	11.69	1.17	3.27	22.65
3	2	344	0.52	1.33	10.51	1.06	2.75	21.21
4	3	424	0.40	0.73	10.56	0.92	1.67	24.32
5	4	515	0.38	0.48	11.99	0.90	1.12	28.16
7	5	584	0.33	0.59	12.89	0.91	1.38	30.50
8	6	675	0.40	1.22	12.34	0.91	2.84	28.77
9	7	755	0.45	3.33	11.37	1.04	7.62	26.07
10	8	835	0.50	8.51	10.44	1.11	18.84	23.10

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*Percent of fuel flow mass per mode.

TABLE C-5. MODAL BRAKE SPECIFIC AND FUEL SPECIFIC EMISSIONS FOR LOW-SAC INJECTORS, STANDARD TIMING, AND WATER INDUCTION (Cont'd)

Mode	Notch Position	Engine Speed, rpm	Grams/Bhp-Hour HC	Grams/Bhp-Hour CO	Grams/Bhp-Hour NO_x	Grams/Pound of Fuel HC	Grams/Pound of Fuel CO	Grams/Pound of Fuel NO_x
	75% Water Induction*							
1, 6, 11	Low Idle	285	-	-	-	5.01	4.61	29.09
2	1	285	0.97	1.51	10.72	1.88	2.93	21.15
3	2	344	0.81	1.13	9.61	1.63	2.26	19.29
4	3	424	0.56	0.63	10.39	1.28	1.45	23.84
5	4	515	0.56	0.41	11.77	1.33	0.97	27.75
7	5	584	0.47	0.47	12.38	1.10	1.12	29.28
8	6	675	0.50	1.04	12.10	1.16	2.43	28.34
9	7	755	0.57	2.97	10.99	1.31	6.88	25.43
10	8	835	0.63	8.20	10.13	1.40	18.46	22.78
	100% Water Induction*							
1, 6, 11	Low Idle	285	-	-	-	6.11	8.80	33.47
2	1	285	0.92	1.85	10.53	1.93	3.88	22.10
3	2	344	0.81	1.35	9.91	1.62	2.69	19.77
4	3	424	0.55	0.77	10.36	1.28	1.81	24.34
5	4	515	0.52	0.59	12.16	1.23	1.39	28.87
7	5	584	0.46	0.74	12.45	1.10	1.76	29.86
8	6	675	0.49	1.35	11.95	1.18	3.26	28.77
9	7	755	0.56	3.64	10.96	1.31	8.59	25.17
10	8	835	0.66	9.92	9.84	1.50	22.38	22.20

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*Percent of fuel flow mass per mode.

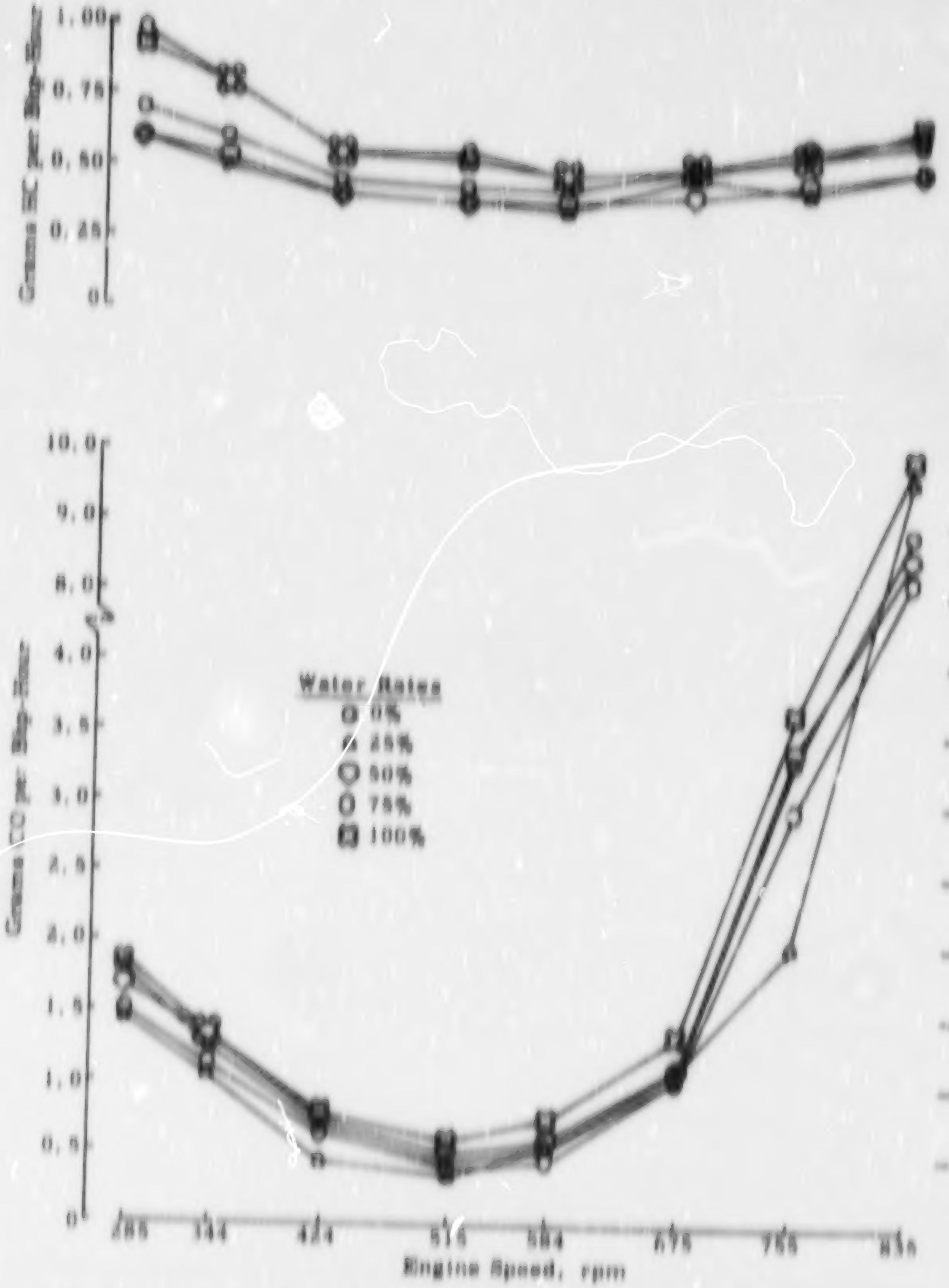

FIGURE C-21. MODAL BRAKE SPECIFIC HC AND CO FOR VARIOUS WATER INDUCTION RATES--LOW-SAC INJECTORS AT STANDARD TIMING

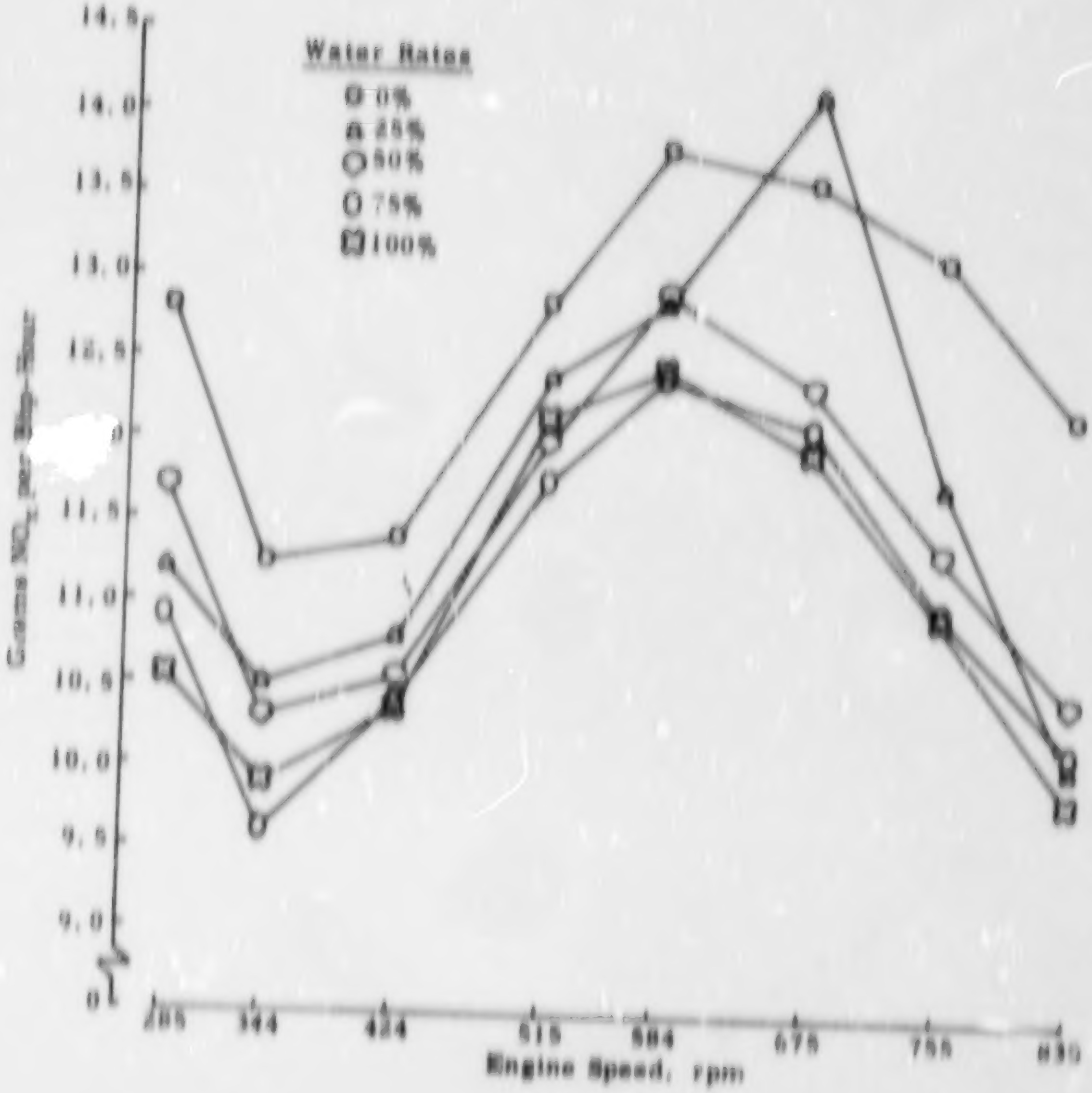

FIGURE C-21. MODAL BRAKE SPECIFIC NO$_x$ FOR VARIOUS WATER INDUCTION RATES--LOW-SAC INJECTORS AT STANDARD TIMING

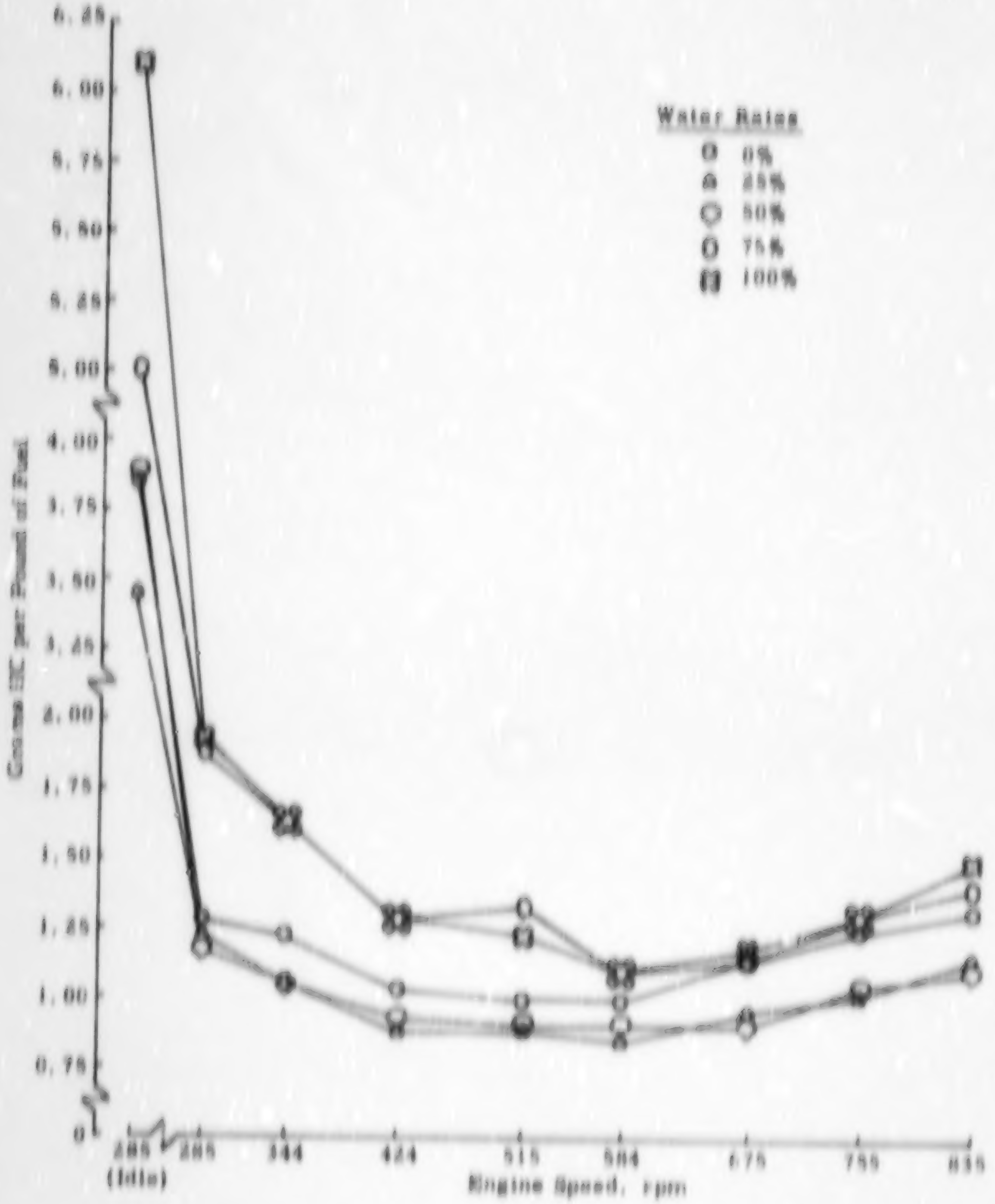

FIGURE C-45. MODAL FUEL SPECIFIC HC FOR VARIOUS WATER INDUCTION RATES--LOW-SAC INJECTORS AT STANDARD TIMING

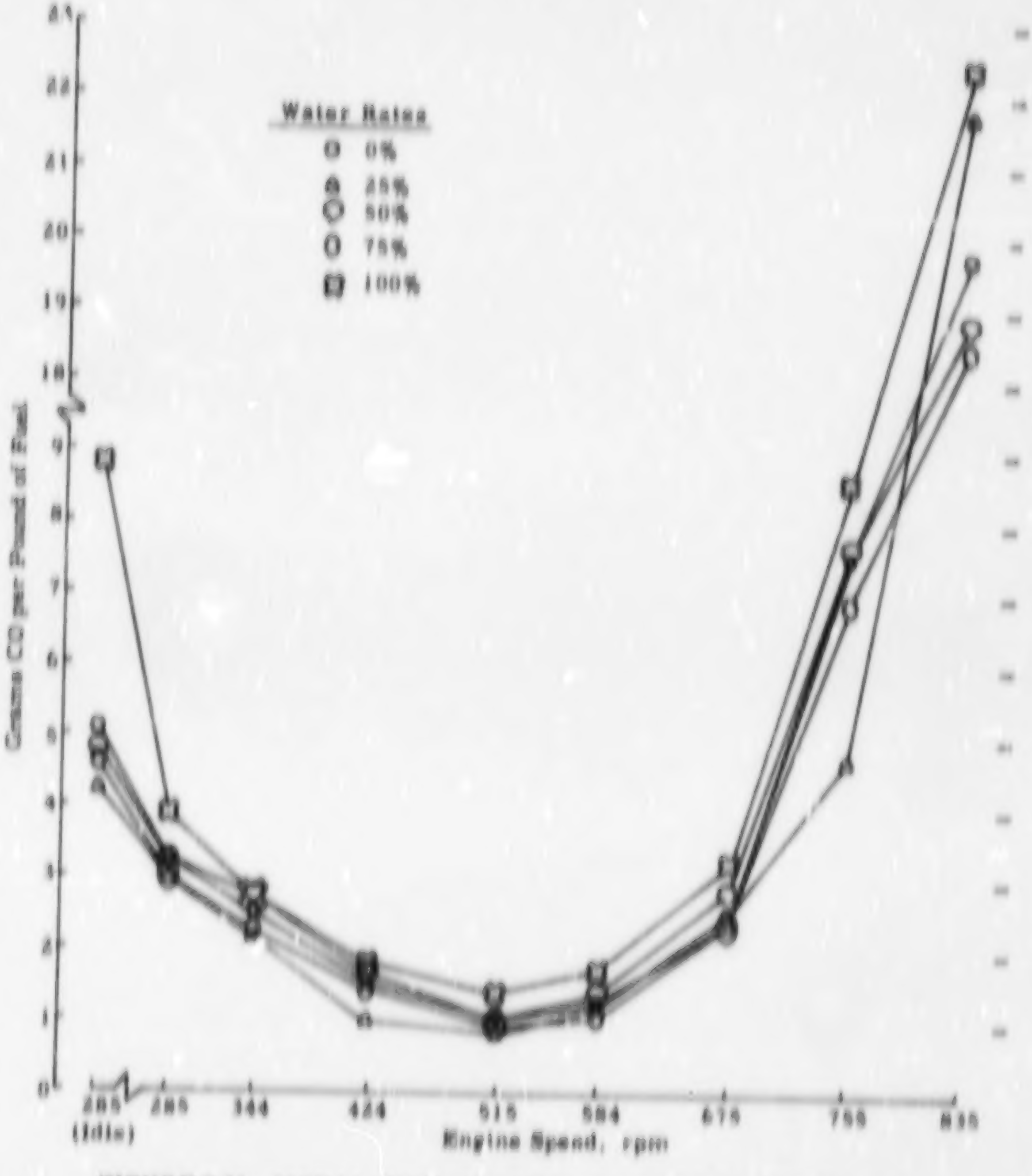

FIGURE C-26. MODAL FUEL SPECIFIC CO FOR VARIOUS WATER INDUCTION RATES--LOW-SAC INJECTORS AT STANDARD TIMING

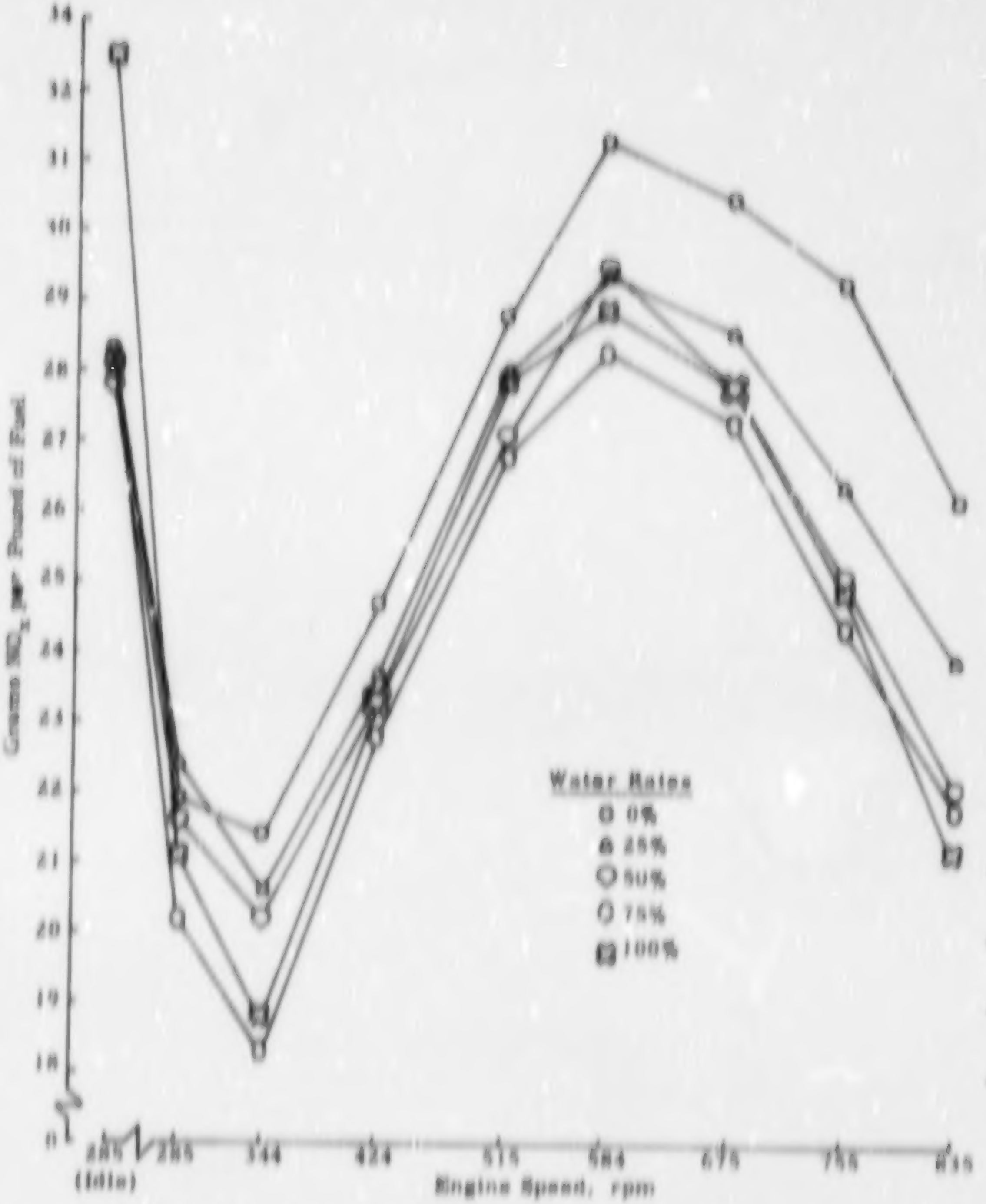

FIGURE C-27. MODAL FUEL SPECIFIC NO_x FOR VARIOUS WATER INDUCTION RATES--LOW-SAC INJECTORS AT STANDARD TIMING

TABLE C-4. MODAL BRAKE SPECIFIC AND FUEL SPECIFIC EMISSIONS FOR NEEDLE-VALVE INJECTORS, RETARDED TIMING, AND WATER INDUCTION

Mode	Engine Speed, rpm	Grams/Bhp-Hour HC	Grams/Bhp-Hour CO	Grams/Bhp-Hour NO_x	Grams/Pound of Fuel HC	Grams/Pound of Fuel CO	Grams/Pound of Fuel NO_x
				0% Water Induction[a]			
1, 6, 11	285	c	c	c	6.15	5.33	15.15
2	285	1.96	2.14	7.75	3.00	3.33	12.07
3	344	1.28	1.51	6.33	2.31	2.77	11.66
4	424	0.90	0.76	6.22	1.90	1.60	13.24
5	515	0.85	0.69	6.84	1.88	1.53	15.21
7	584	0.78	1.34	7.01	1.76	3.06	15.91
8	675	0.77	2.65	7.56	1.75	6.03	17.11
9	755	0.90	6.62	7.26	2.03	14.81	16.23
10	835	0.88	14.52	6.93	1.89	31.10	14.84
				25% Water Induction[a]			
1, 6, 11	285	c	c	c	5.63	4.01	17.52
2	285	1.16	1.42	6.54	2.08	2.54	11.72
3	344	0.94	1.10	5.50	1.82	2.13	10.72
4	424	0.72	0.58	5.62	1.49	1.18	11.62
5	515	0.70	0.67	6.04	1.52	1.44	13.00
7	584	0.72	1.44	6.08	1.60	3.18	13.49
8	675	0.80	3.25	6.03	1.76	7.17	13.27
9	755	0.97	6.82	5.92	2.10	14.86	12.80
10	835	1.48	17.02	5.84	3.13	35.92	11.69
				50% Water Induction[a]			
1, 6, 11	285	c	c	c	5.50	6.01	17.10
2	285	1.16	2.22	5.58	2.21	4.25	10.68
3	344	1.03	1.72	5.22	1.78	3.14	10.10
4	424	0.75	1.08	5.12	1.62	2.36	11.15
5	515	0.74	1.07	5.74	1.61	2.37	12.71
7	584	0.72	2.10	5.85	1.59	4.68	13.04
8	675	0.80	3.68	6.06	1.77	8.10	13.36
9	755	0.84	7.78	5.60	1.92	17.12	12.34
10	835	1.19	18.34	5.13	2.50	38.58	10.80
				75% Water Induction[a]			
1, 6, 11	285	c	c	c	5.64	6.34	17.11
2	285	1.06	1.62	5.49	2.00	3.08	10.40
3	344	0.98	1.48	5.04	1.88	2.86	9.70
4	424	0.73	0.72	4.88	1.56	1.55	10.40
5	515	0.72	0.91	5.49	1.56	1.98	12.00
7	584	0.71	1.76	5.82	1.52	3.92	12.92
8	675	0.78	3.56	5.72	1.74	7.86	12.66
9	755	0.88	7.60	5.36	1.90	16.48	11.52
10	835	1.14	17.90	4.79	2.40	37.50	10.06

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[a] Percent of fuel flow mass per mode.

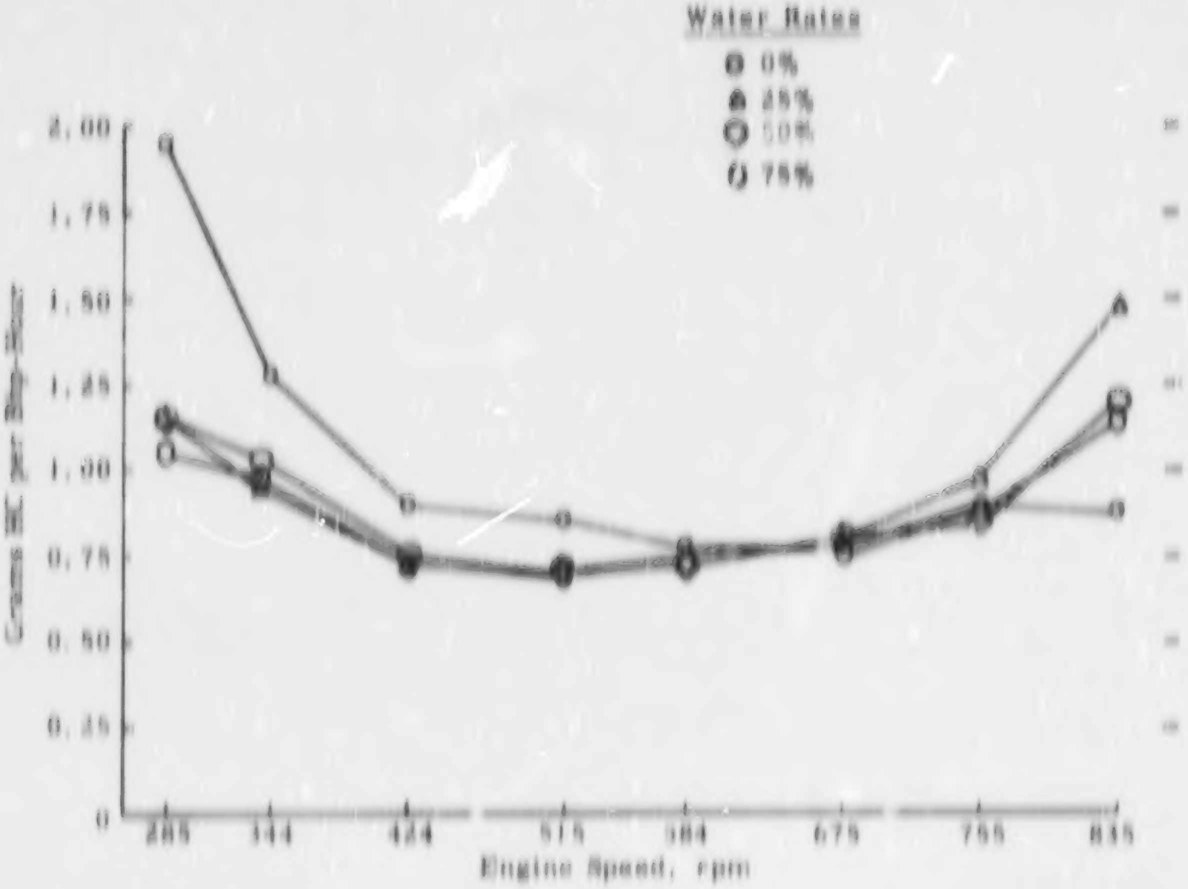

FIGURE C-28.MODAL BRAKE SPECIFIC HC FOR VARIOUS WATER INDUCTION RATES--NEEDLE-VALVE INJECTORS AT RETARDED TIMING

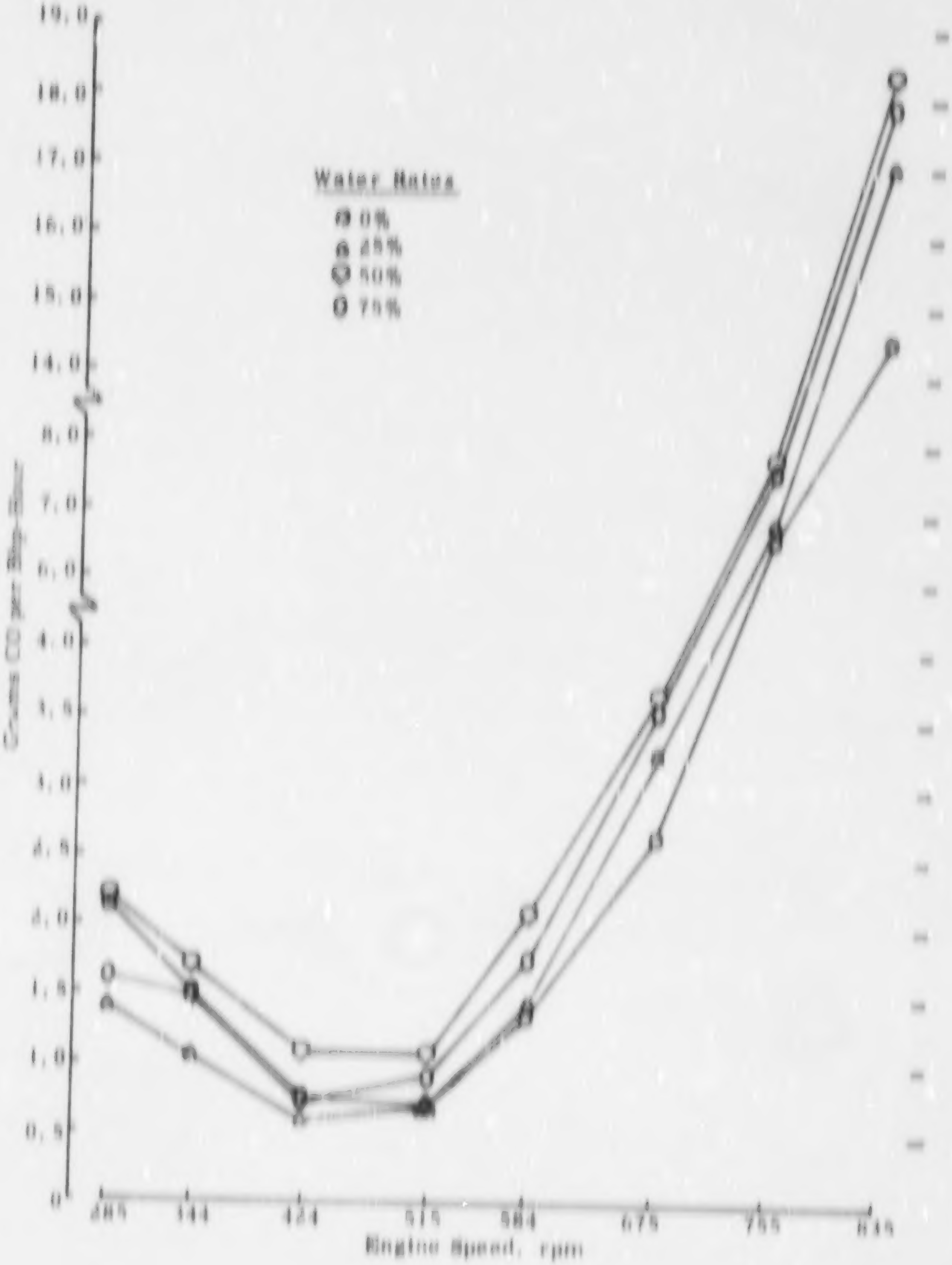

FIGURE C-29 MODAL BRAKE SPECIFIC CO FOR VARIOUS WATER INDUCTION RATES--NEEDLE-VALVE INJECTORS AT RETARDED TIMING

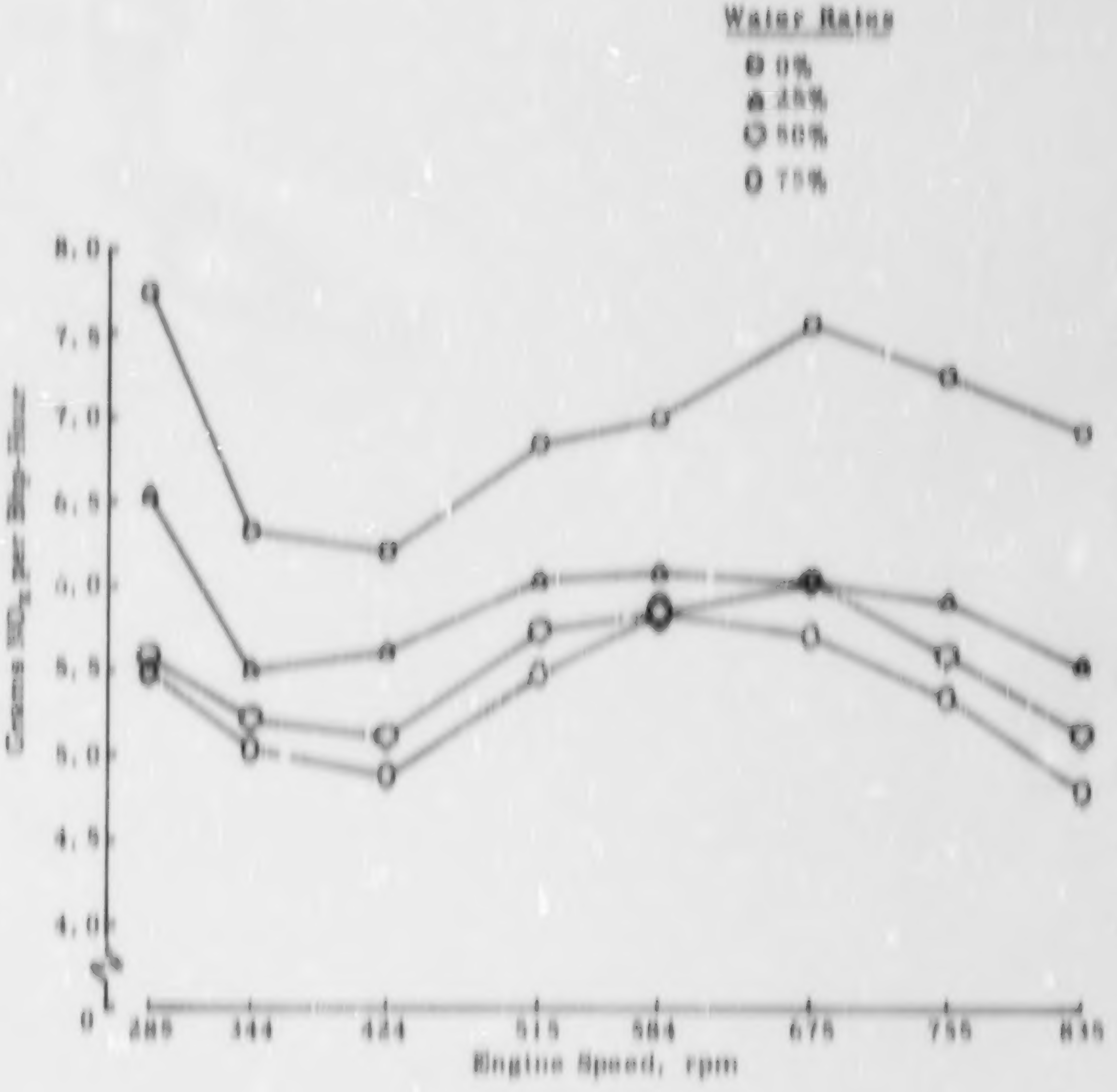

FIGURE C-39. MODAL BRAKE SPECIFIC NO$_x$ FOR VARIOUS WATER INDUCTION RATES--NEEDLE-VALVE INJECTORS AT RETARDED TIMING

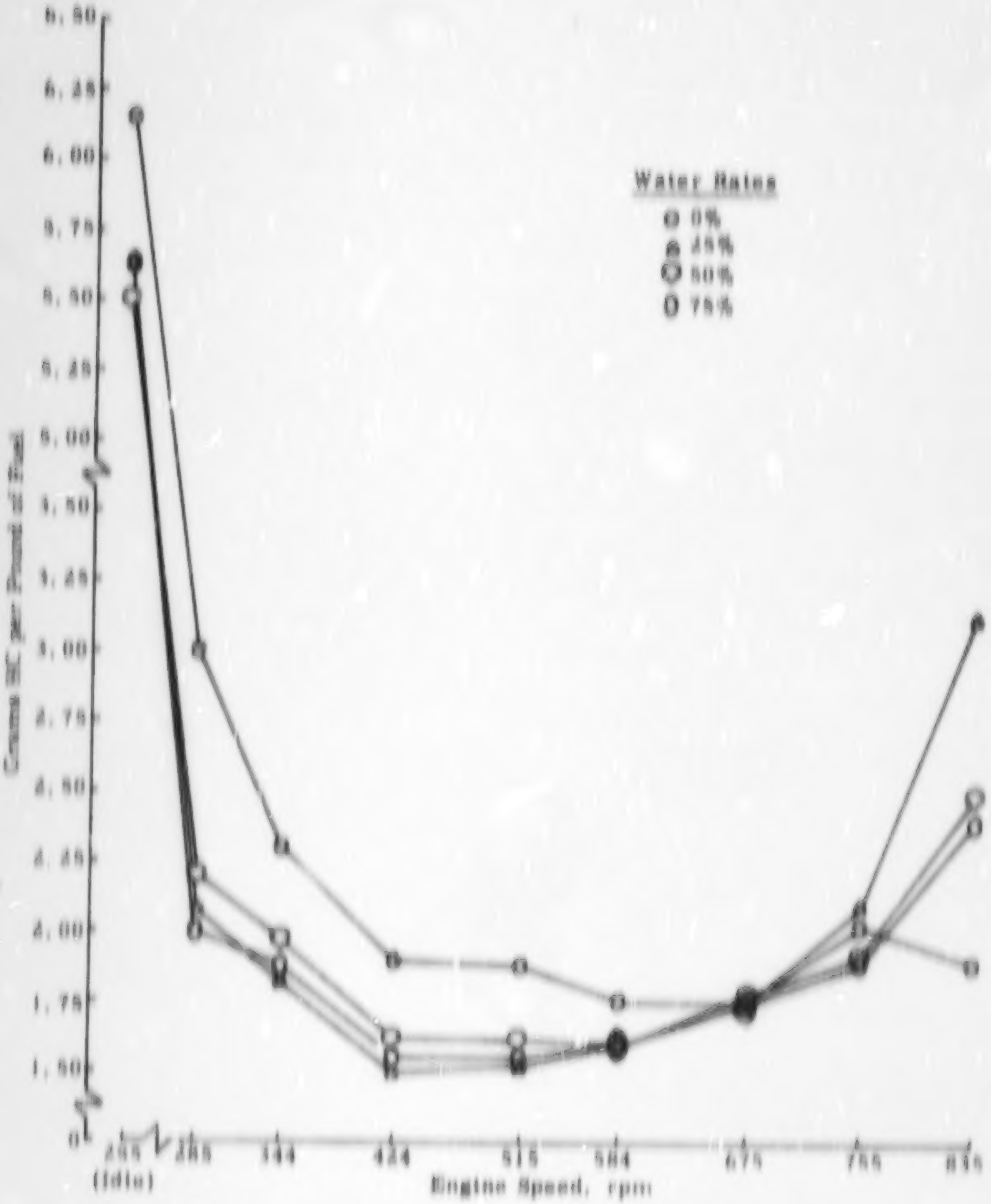

FIGURE C-31. MODAL FUEL SPECIFIC HC FOR VARIOUS WATER INDUCTION RATES--NEEDLE-VALVE INJECTORS AT RETARDED TIMING

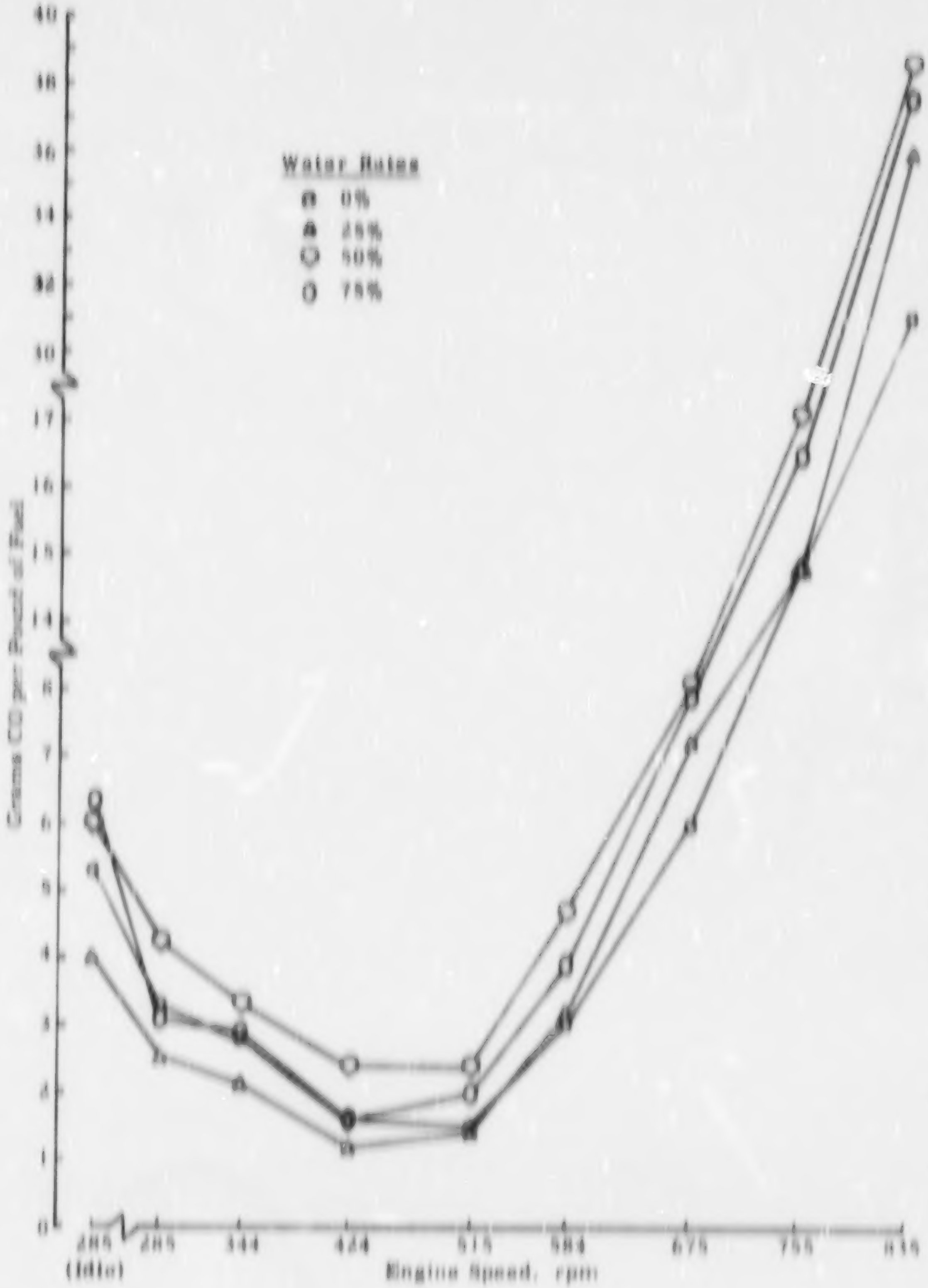

FIGURE C-[illegible]2. MODAL FUEL SPECIFIC CO FOR VARIOUS WATER INDUCTION RATES--NEEDLE-VALVE INJECTORS AT RETARDED TIMING

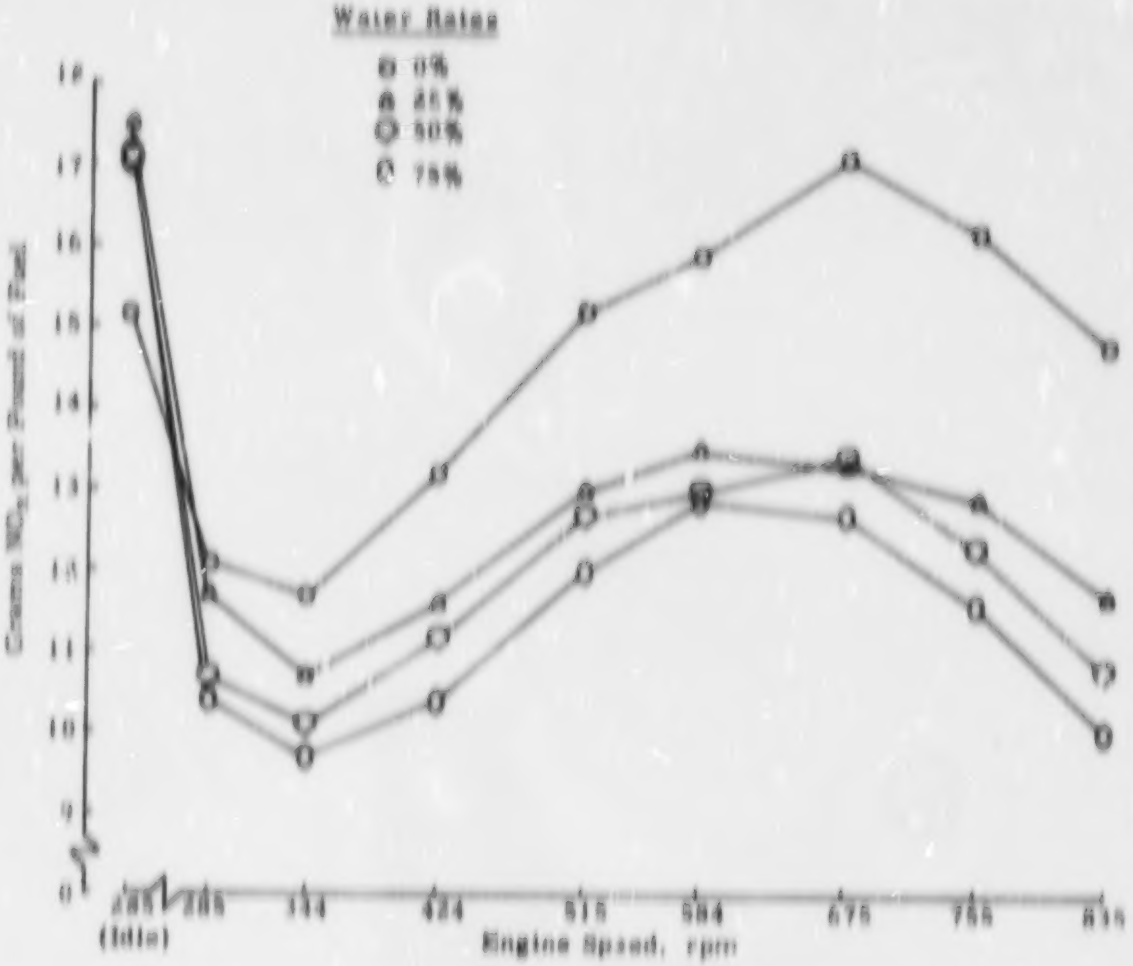

FIGURE C-33. MODAL FUEL SPECIFIC NO_x FOR VARIOUS WATER INDUCTION RATES--NEEDLE-VALVE INJECTORS AT RETARDED TIMING

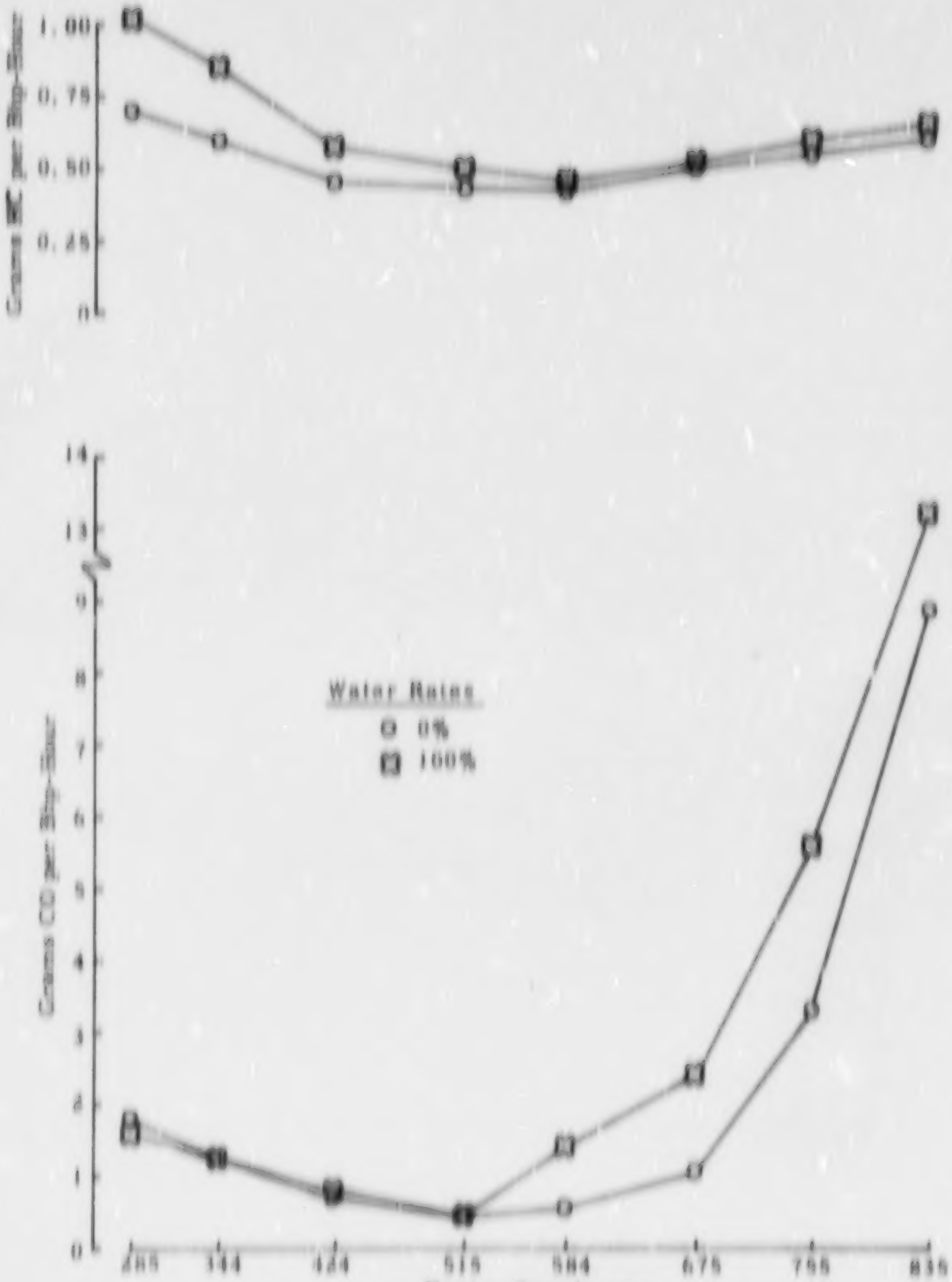

FIGURE C-14. MODAL BRAKE SPECIFIC HC AND CO FOR OPTIMUM WATER INDUCTION RATE -- LOW-SAC INJECTORS AT RETARDED TIMING

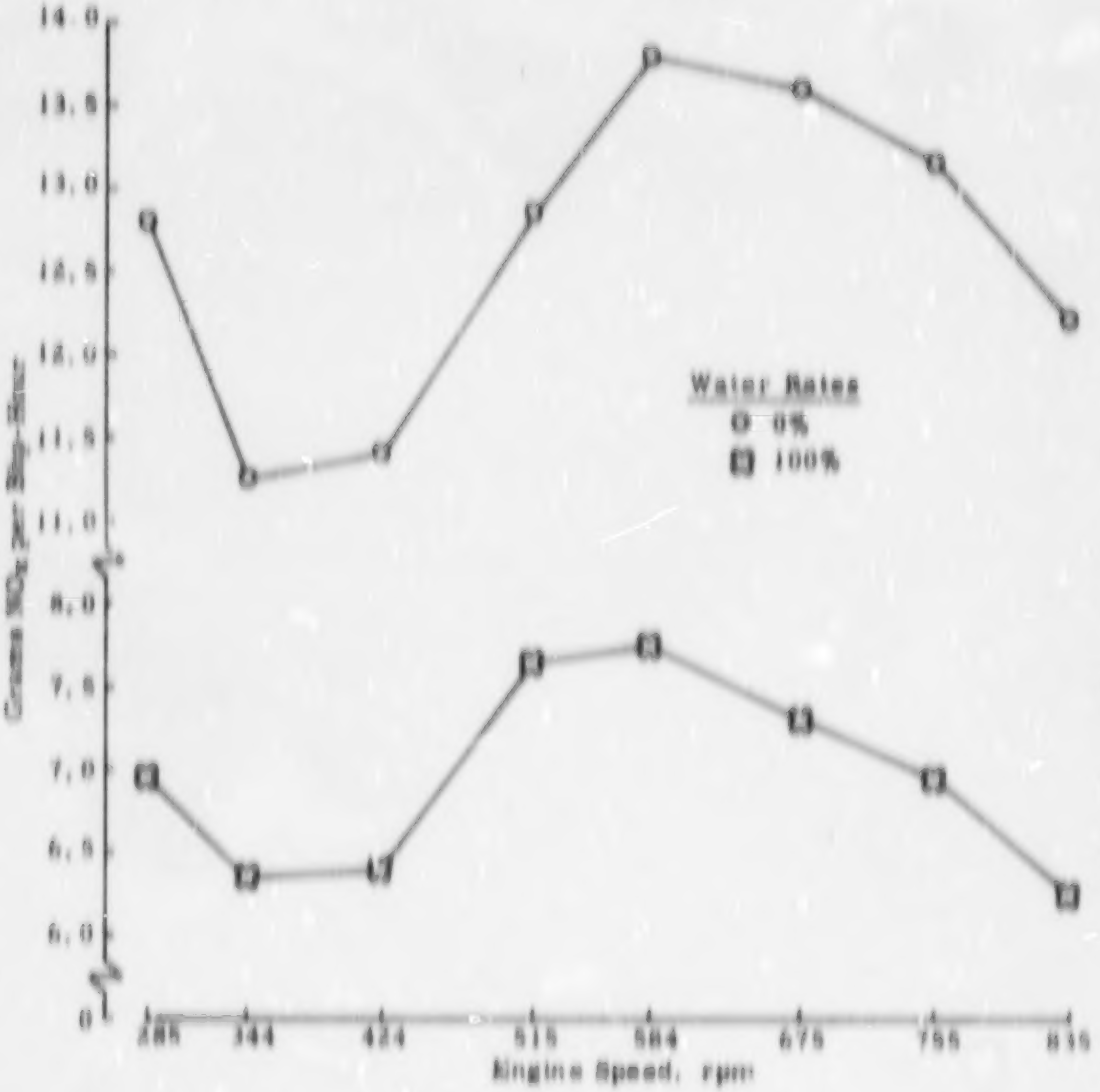

FIGURE C-35. MODAL BRAKE SPECIFIC NO_x FOR OPTIMUM WATER INDUCTION RATE --LOW-SAC INJECTORS AT RETARDED TIMING

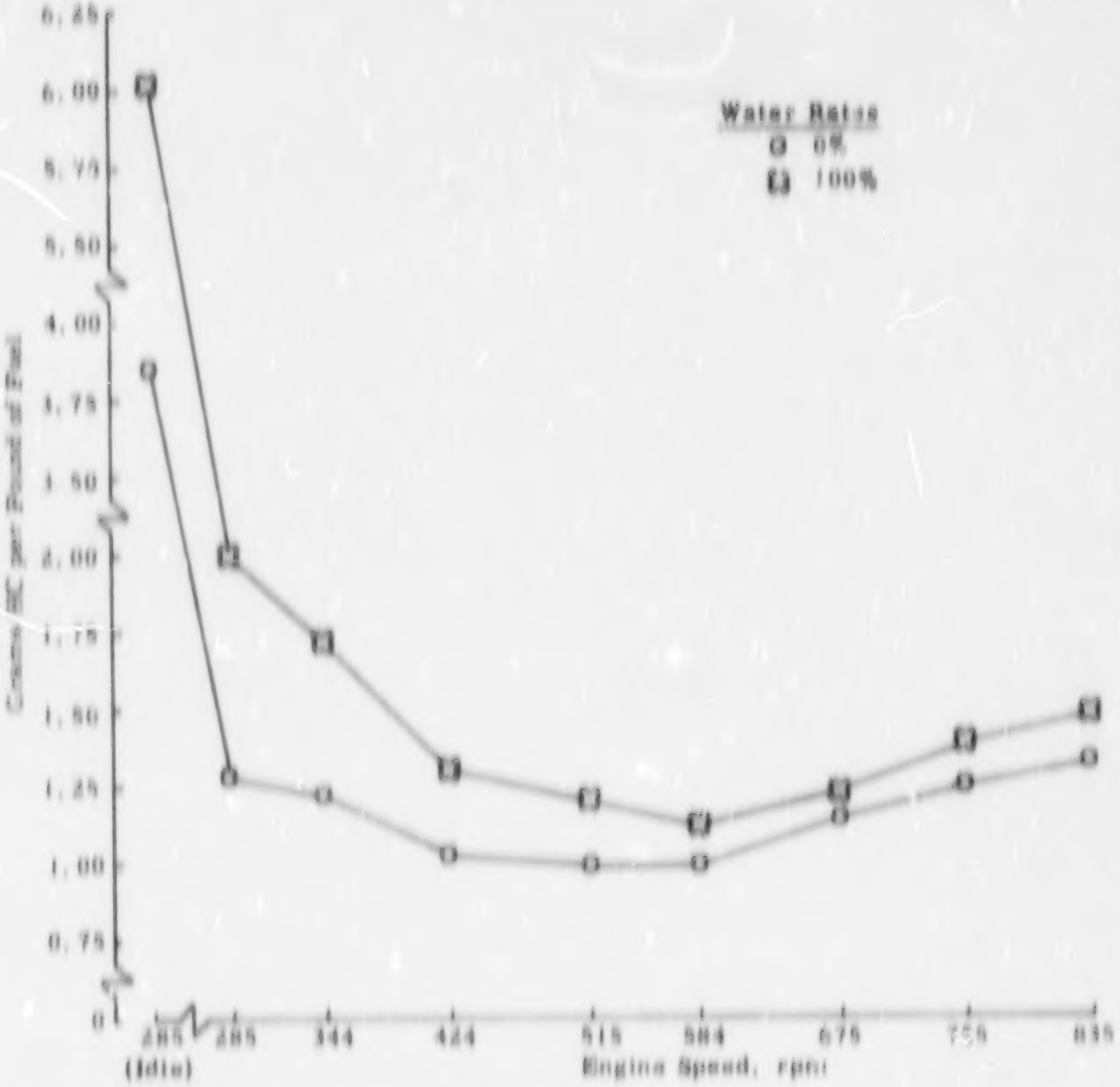

FIGURE C-36. MODAL FUEL SPECIFIC HC FOR OPTIMUM WATER INDUCTION RATE --LOW-SAC INJECTORS AT RETARDED TIMING

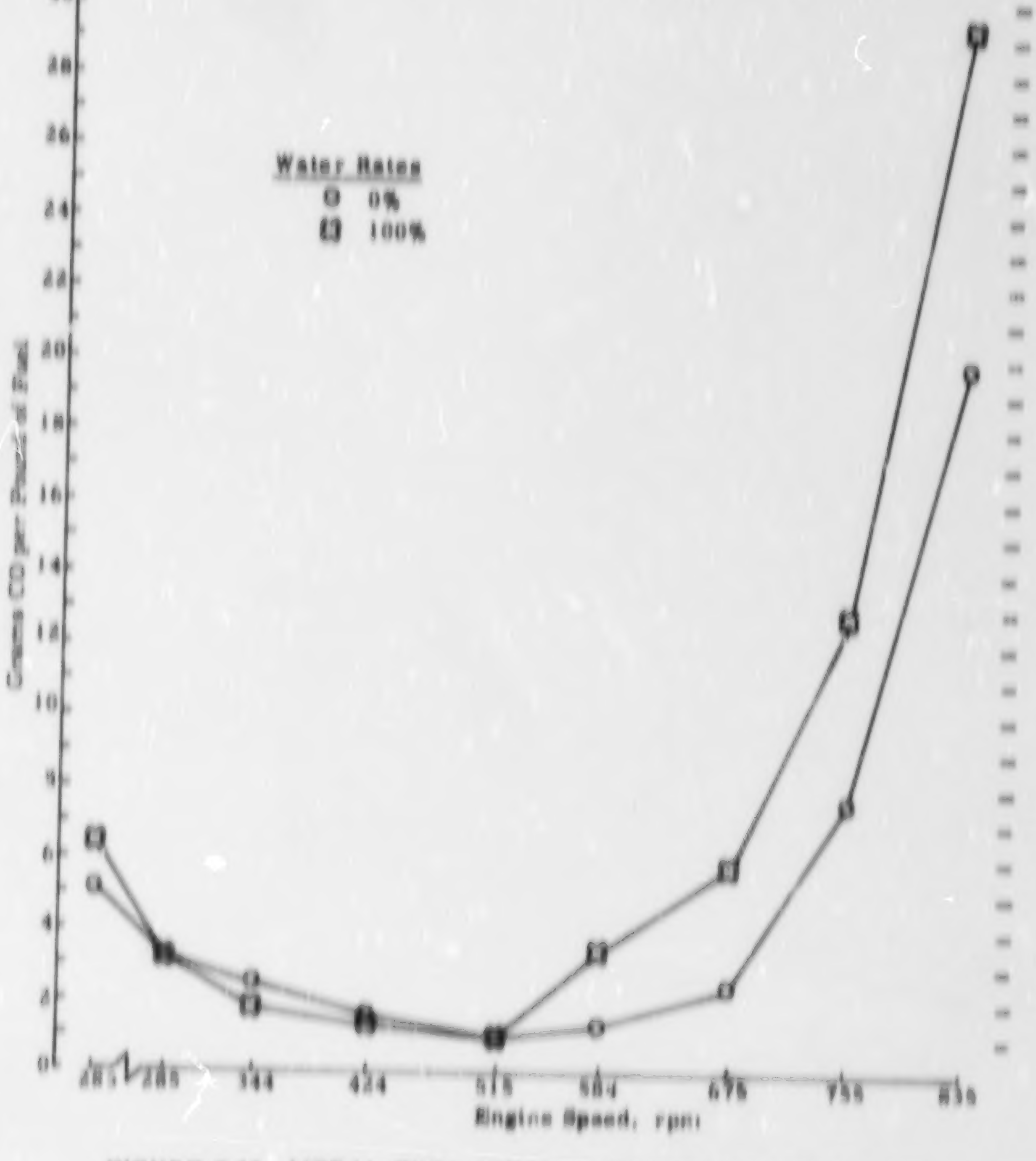

FIGURE C-37. MODAL FUEL SPECIFIC CO FOR OPTIMUM WATER INDUCTION RATE - - LOW-SAC INJECTORS AT RETARDED TIMING

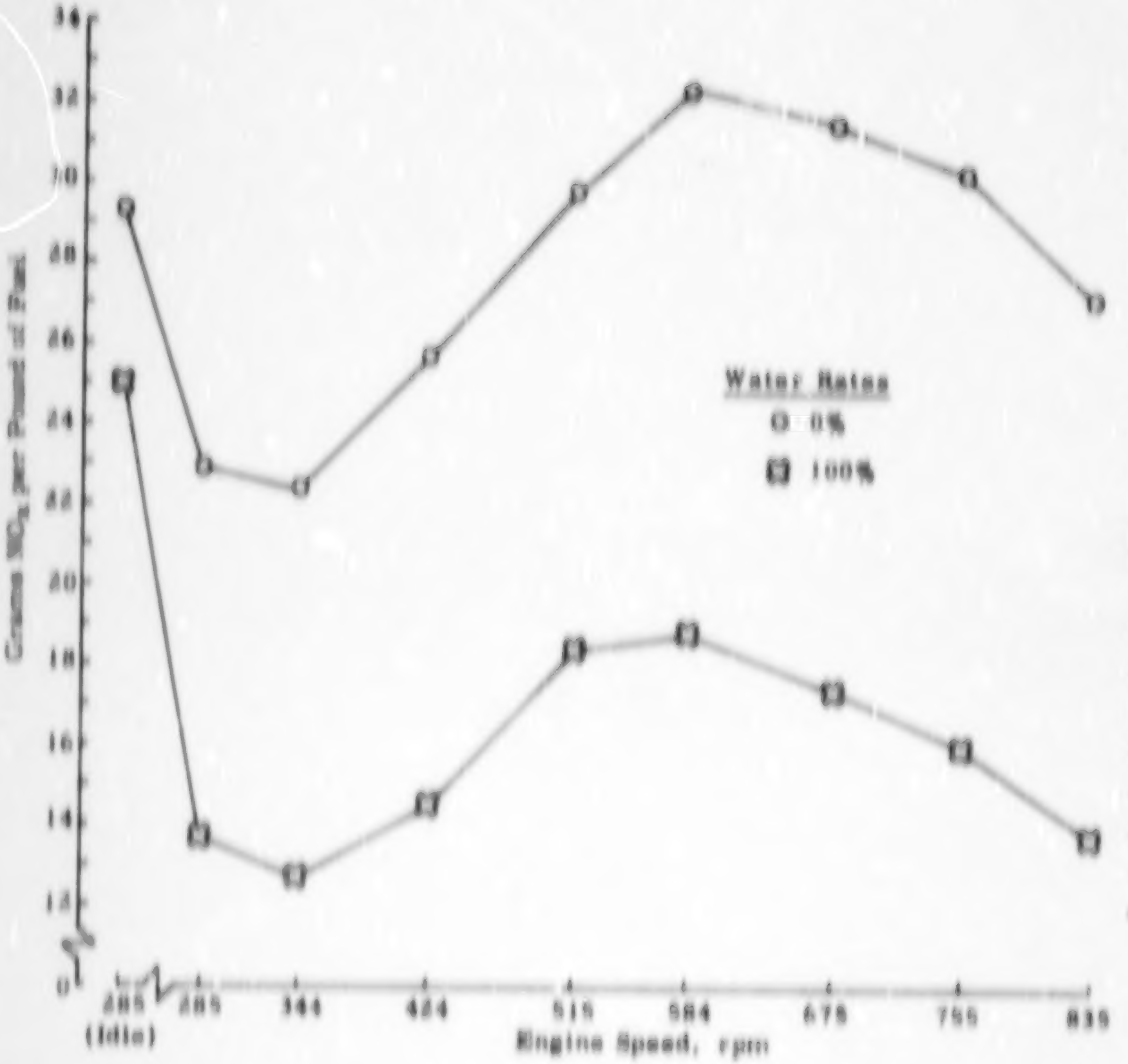

FIGURE C-38. MODAL FUEL SPECIFIC NO_x FOR OPTIMUM WATER INDUCTION RATE--LOW-SAC INJECTORS AT RETARDED TIMING

TABLE C-7. SUMMARY OF EMISSION CONCENTRATIONS FOR VARIOUS RATES OF AIR BOX BLEED-- NEEDLE INJECTORS AT STANDARD TIMING

Mode	Engine Speed, rpm	Air Box Bleed Rates* 0%	10%	20%	35%	50%
		HC Concentrations, ppmC				
1, 6, 11	285	142	117	99	86	109
2	285	128	114	106	84	136
3	344	139	128	116	92	152
4	424	154	148	130	110	182
5	515	176	166	144	130	216
7	584	184	196	168	152	229
8	675	232	232	196	174	180
9	755	272	262	306	154	126
10	835	288	438	266	176	94
		CO Concentrations, ppm				
1, 6, 11	285	59	54	34	48	63
2	285	66	71	71	65	117
3	344	77	56	82	65	110
4	424	63	52	75	69	147
5	515	58	52	86	96	354
7	584	82	131	171	383	1493
8	675	252	358	500	1025	3571
9	755	800	957	1329	2284	4278
10	835	1999	2386	3031	3758	6157
		NO_x Concentrations, ppm				
1, 6, 11	285	128	136	133	143	147
2	285	162	226	219	229	229
3	344	219	277	270	277	258
4	424	375	427	387	363	315
5	515	540	548	499	486	445
7	584	733	708	647	636	551
8	675	842	809	745	675	566
9	755	870	865	821	763	632
10	835	874	897	826	742	637

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*Percent of air flow mass requirement per mode.

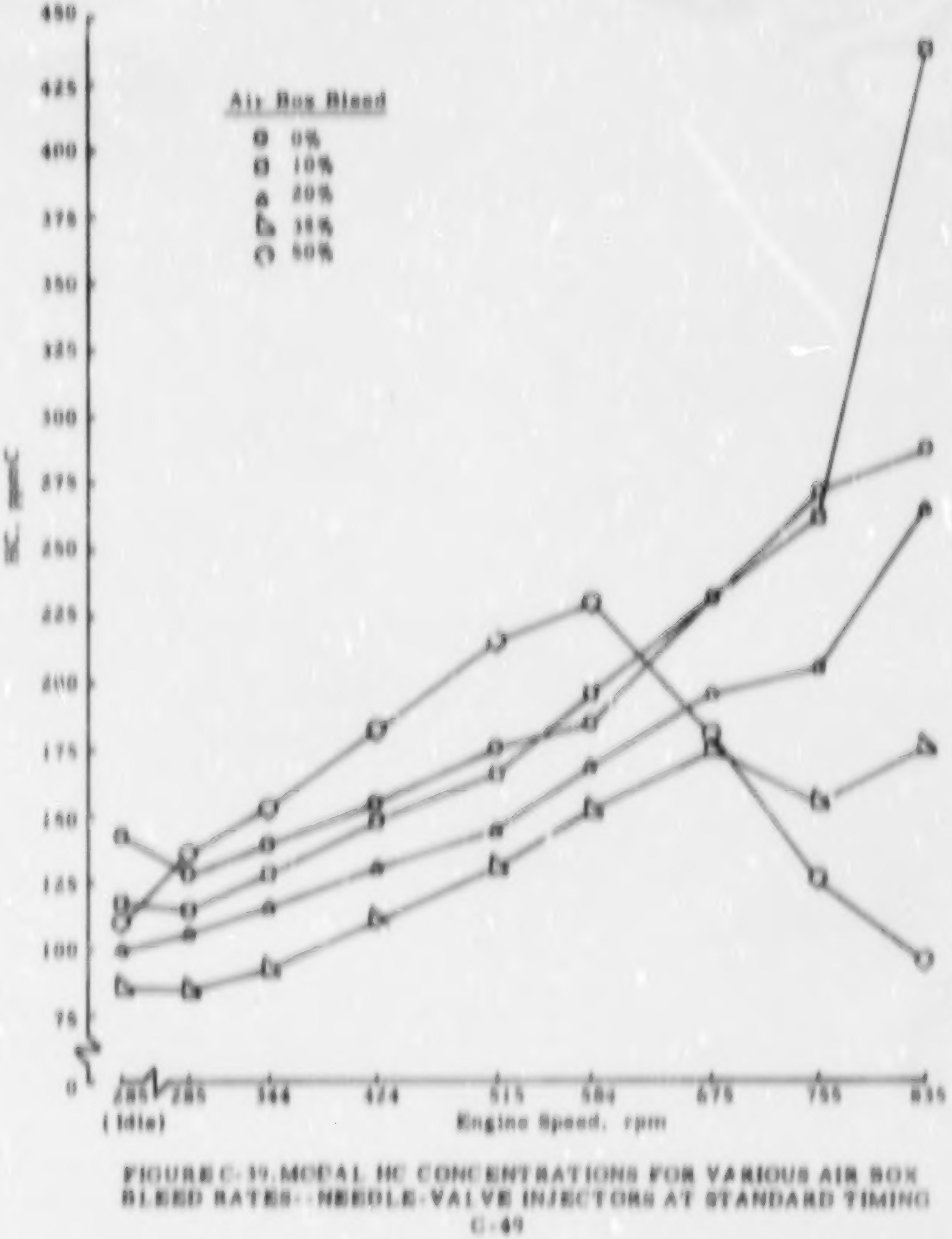

FIGURE C-19. MODAL HC CONCENTRATIONS FOR VARIOUS AIR BOX BLEED RATES--NEEDLE-VALVE INJECTORS AT STANDARD TIMING

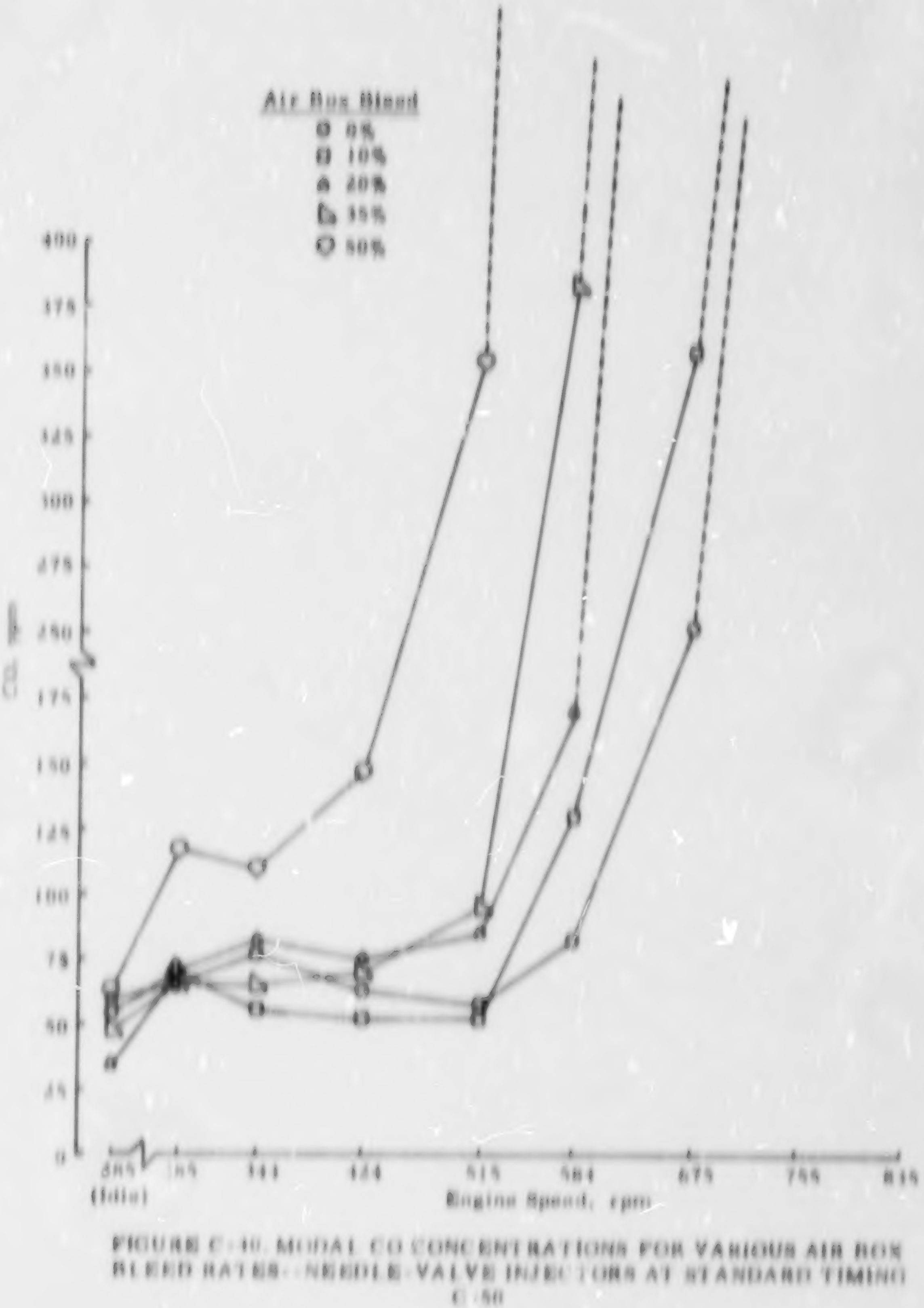

FIGURE C-40. MODAL CO CONCENTRATIONS FOR VARIOUS AIR BOX BLEED RATES--NEEDLE-VALVE INJECTORS AT STANDARD TIMING

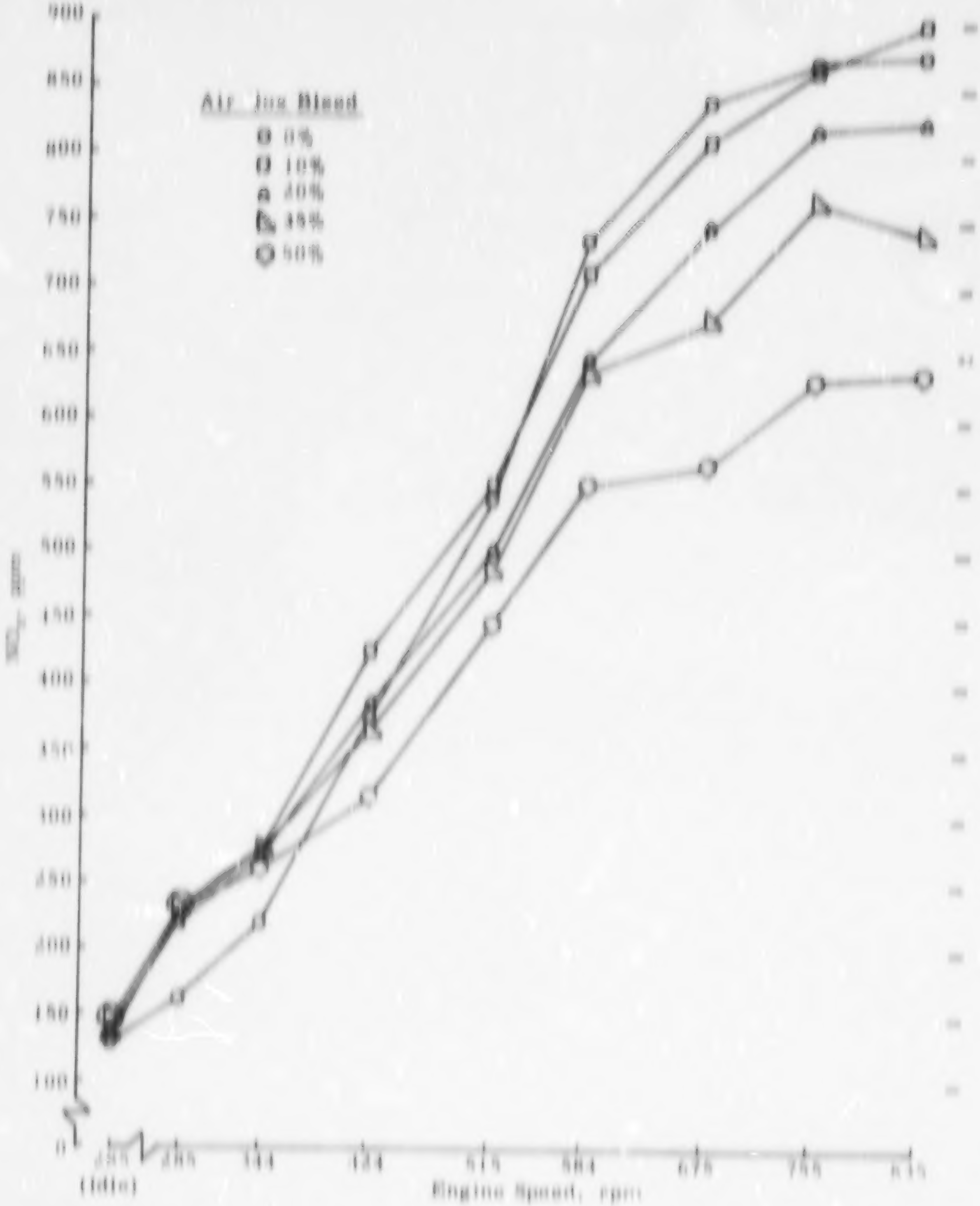

FIGURE C-41. MODAL NO_x CONCENTRATIONS FOR VARIOUS AIR BOX BLEED RATES--NEEDLE-VALVE INJECTORS AT STANDARD TIMING

TABLE C-8. SUMMARY OF EMISSION CONCENTRATIONS FOR VARIOUS RATES OF AIR BOX BLEED--LOW-SAC INJECTORS AT STANDARD TIMING

Mode	Engine Speed, rpm	Air Box Bleed Rates* 0%	20%	35%
		HC Concentrations, ppmC		
1, 6, 11	285	68	83	69
2	285	49	80	72
3	344	61	96	78
4	424	72	116	88
5	515	81	122	102
7	584	93	152	122
8	675	125	182	126
9	755	151	176	160
10	835	181	178	161
		CO Concentrations, ppm		
1, 6, 11	285	45	44	63
2	285	63	77	94
3	344	53	88	93
4	424	54	92	120
5	515	42	120	351
7	584	65	258	1004
8	675	133	685	2087
9	755	459	1822	3436
10	835	1355	3539	3919
		NO_x Concentrations, ppm		
1, 6, 11	285	158	172	168
2	285	271	279	282
3	344	342	316	316
4	424	549	492	419
5	515	750	668	591
7	584	971	827	695
8	675	1058	941	728
9	755	1121	992	780
10	835	1136	934	809

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*Percent of engine air flow mass requirement per mode.

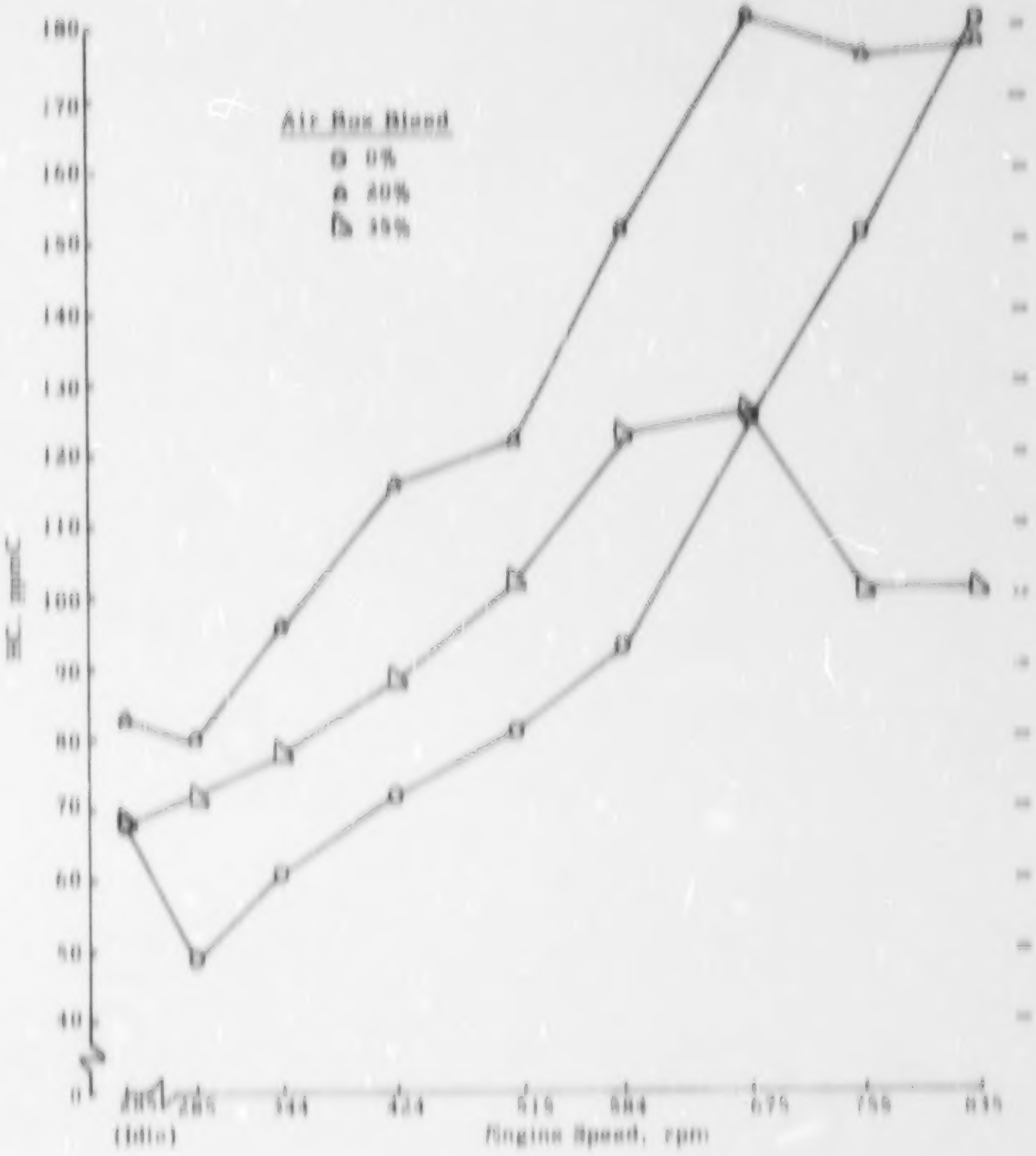

FIGURE C-42. MODAL HC CONCENTRATIONS FOR VARIOUS AIR BOX BLEED RATES--LOW-SAC INJECTORS AT STANDARD TIMING

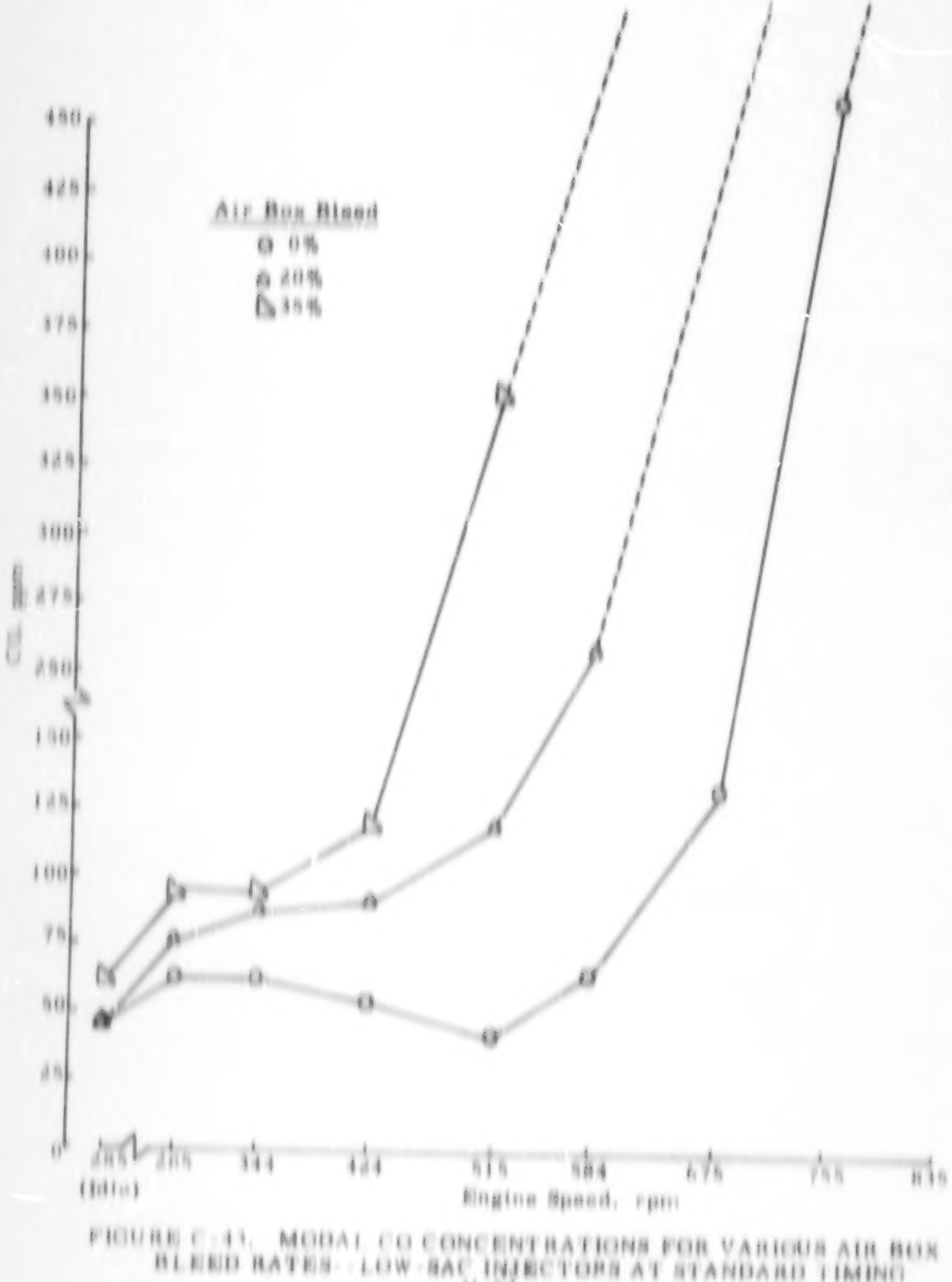

FIGURE C-41. MODAL CO CONCENTRATIONS FOR VARIOUS AIR BOX BLEED RATES - LOW-SAC INJECTORS AT STANDARD TIMING

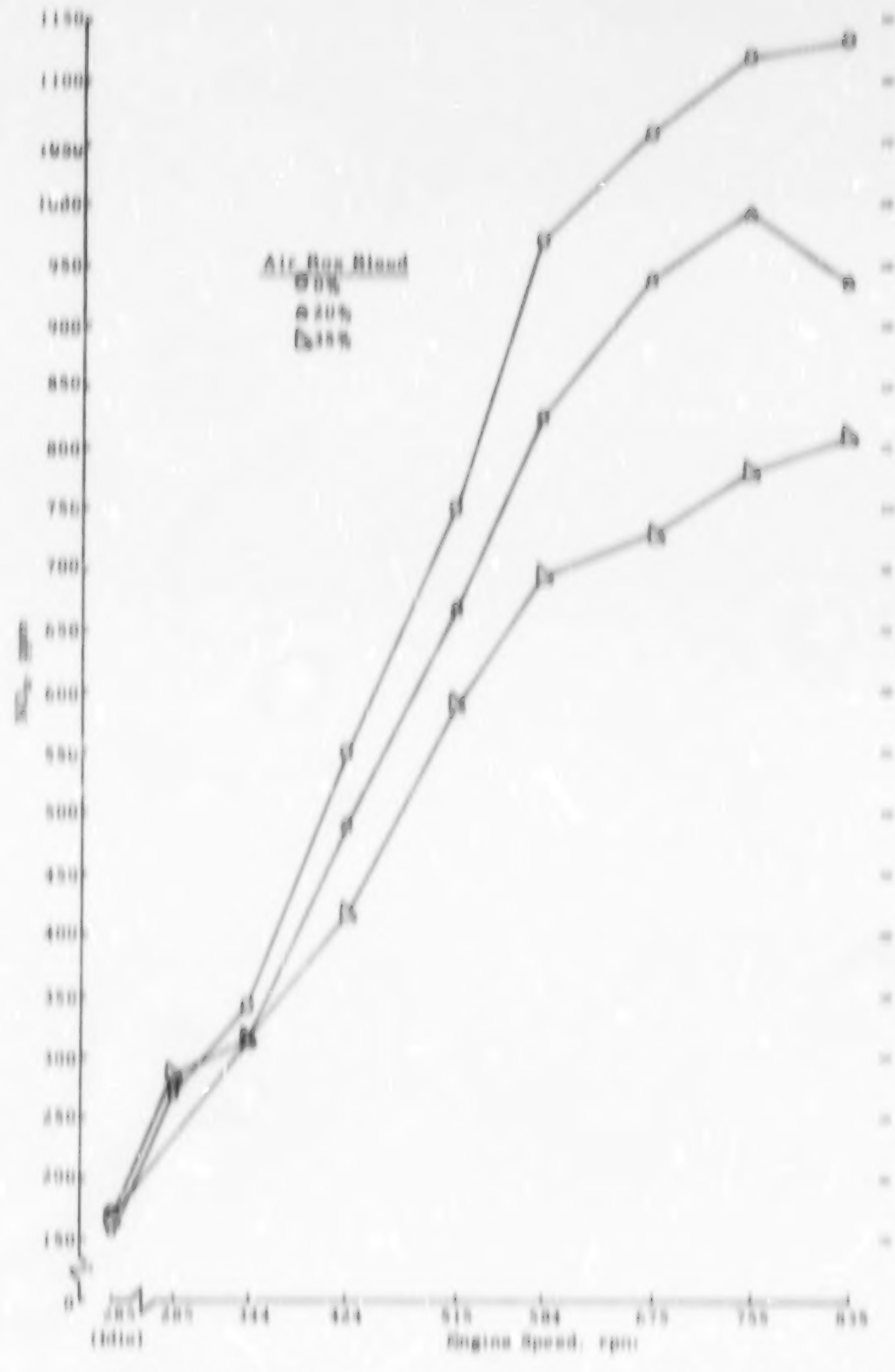

FIGURE C-41. MODAL NO_x CONCENTRATIONS FOR VARIOUS AIR BOX BLEED RATES--LOW-SAC INJECTORS AT STANDARD TIMING

TABLE C-9. MODAL BRAKE SPECIFIC AND FUEL SPECIFIC EMISSIONS FOR NEEDLE-VALVE INJECTORS, STANDARD TIMING, AND AIR BOX BLEED

Mode	Engine Speed, rpm	Grams/Bhp-Hour HC	Grams/Bhp-Hour CO	Grams/Bhp-Hour NO_x	Grams/Pound of Fuel HC	Grams/Pound of Fuel CO	Grams/Pound of Fuel NO_x
			0% Air Bleed*				
1, 6, 11	285				5.67	6.60	16.52
2	285	3.51	3.70	14.51	3.34	3.65	16.61
3	344	1.80	2.06	7.22	2.68	3.05	13.75
4	424	1.06	0.85	8.47	2.07	1.68	16.56
5	515	0.74	0.51	9.41	1.55	1.28	19.65
7	584	0.81	0.70	10.17	1.71	1.53	22.27
8	675	0.69	1.92	10.52	1.74	4.20	23.00
9	755	0.93	5.06	9.75	2.03	11.09	21.28
10	835	0.92	12.70	9.12	1.92	26.55	19.06
			10% Air Bleed*				
1, 6, 11	285				5.76	5.52	22.07
2	285	1.86	1.81	1.54	2.59	3.20	16.86
3	344	1.18	1.08	8.38	2.28	2.06	16.15
4	424	0.86	0.60	8.17	1.84	1.29	17.37
5	515	0.82	0.51	8.83	1.77	1.10	19.16
7	584	0.78	1.04	9.26	1.74	2.33	21.10
8	675	0.84	2.57	9.52	1.88	5.64	20.92
9	755	0.86	6.26	9.20	1.90	13.76	20.80
10	830	1.28	13.85	8.54	2.76	30.02	18.52
			20% Air Bleed*				
1, 6, 11	285				6.60	3.19	21.44
2	285	1.24	1.65	8.33	2.26	3.00	15.28
3	344	0.98	1.40	7.48	1.90	2.72	14.48
4	424	0.70	0.80	6.78	1.65	1.88	16.13
5	515	0.66	0.78	7.44	1.40	1.66	15.84
7	584	0.62	1.26	7.86	1.35	2.76	17.16
8	675	0.65	3.30	8.05	1.40	7.14	17.46
9	755	0.63	8.08	8.20	1.34	17.22	17.48
10	835	0.76	17.22	7.70	1.54	34.85	15.60
			35% Air Bleed*				
1, 6, 11	285				3.21	4.23	20.77
2	285	0.84	1.40	7.40	1.54	2.58	13.76
3	344	0.68	1.04	6.15	1.33	2.03	12.14
4	424	0.52	0.64	5.56	1.07	1.34	11.55
5	515	0.47	0.72	5.93	1.06	1.53	12.67
7	584	0.47	2.45	6.67	1.02	5.16	13.90
8	675	0.50	5.89	6.37	1.07	12.51	13.55
9	755	0.40	12.01	6.50	0.85	25.08	13.77
10	835	0.45	17.04	6.23	0.87	36.92	13.06
			50% Air Bleed*				
1, 6, 11	285				4.05	4.61	17.90
2	285	1.14	1.33	6.22	2.08	3.58	11.61
3	344	0.92	1.31	5.08	1.76	2.53	9.77
4	424	0.70	1.13	3.98	1.37	2.20	7.76
5	515	0.67	2.25	4.53	1.41	4.58	9.46
7	584	0.60	7.61	4.73	1.23	15.95	9.59
8	675	0.46	17.37	4.68	0.91	35.50	9.37
9	755	0.28	18.61	3.58	0.56	37.15	7.07
10	835	0.21	28.68	4.60	0.37	13.37	8.20

*Percent of air flow mass requirement per mode.

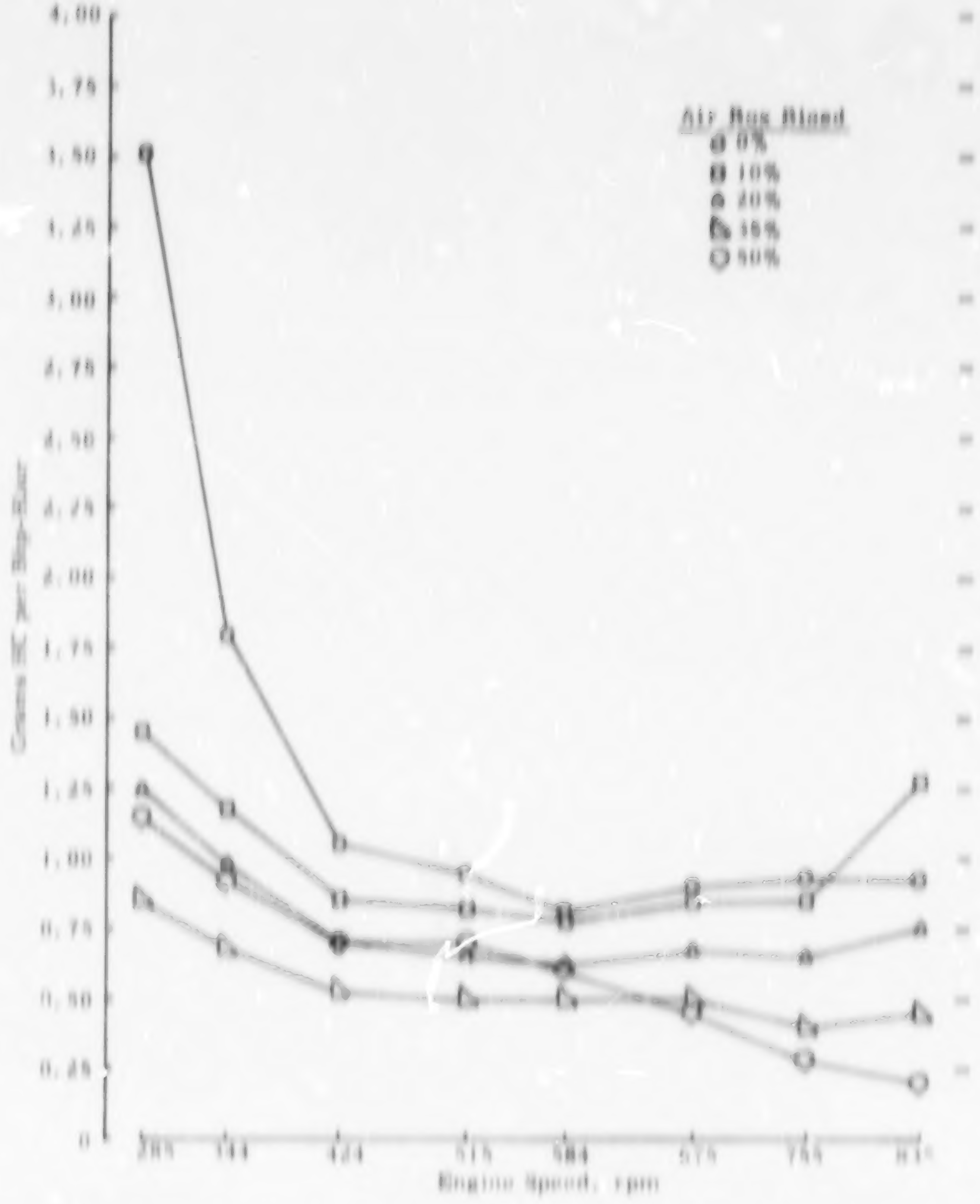

FIGURE C-6. MODAL BRAKE SPECIFIC HC FOR VARIOUS AIR BOX BLEED RATES--NEEDLE-VALVE INJECTORS AT STANDARD TIMING

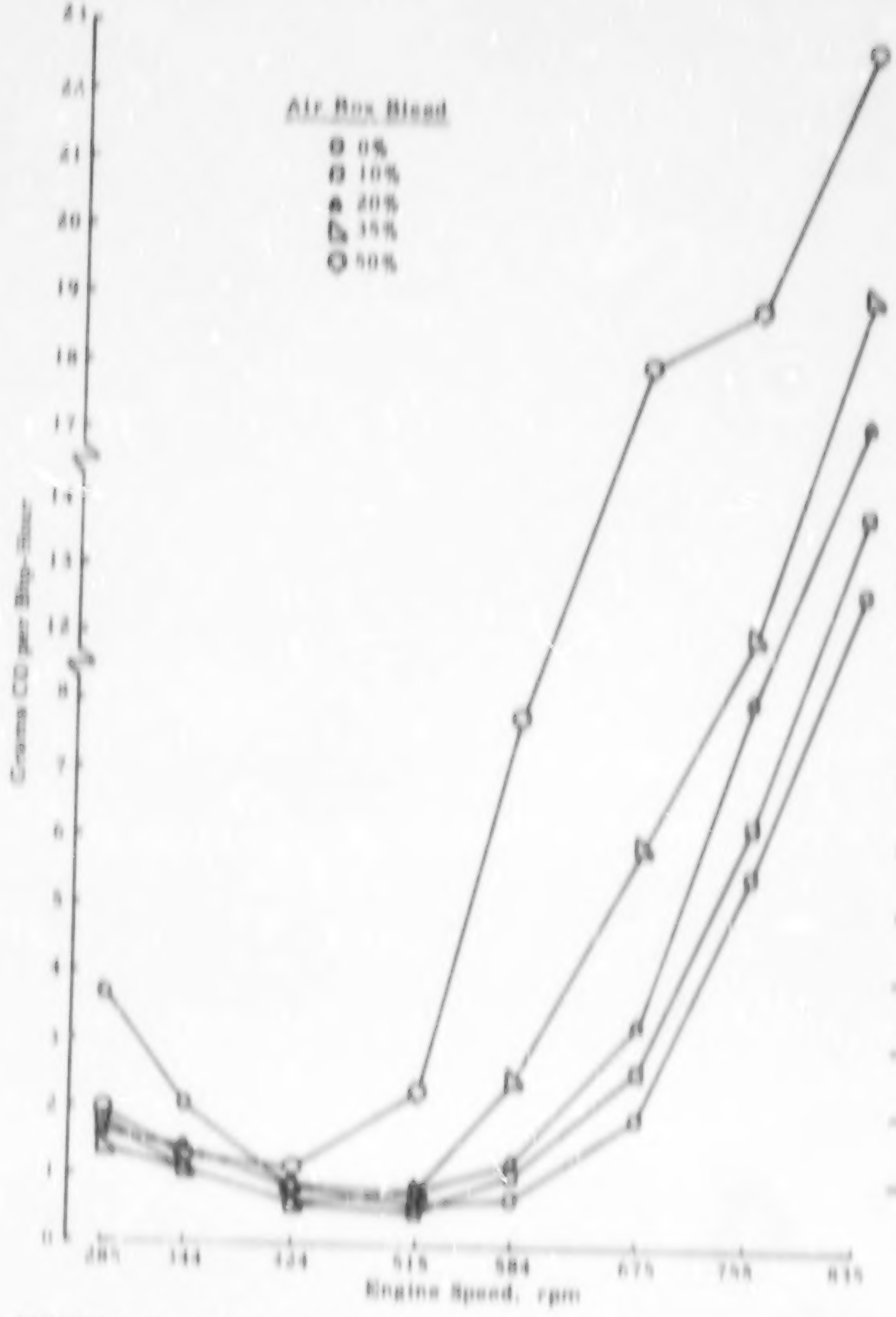

FIGURE C-45. MODAL BRAKE SPECIFIC CO FOR VARIOUS AIR BOX BLEED RATES: NEEDLE-VALVE INJECTORS AT STANDARD TIMING

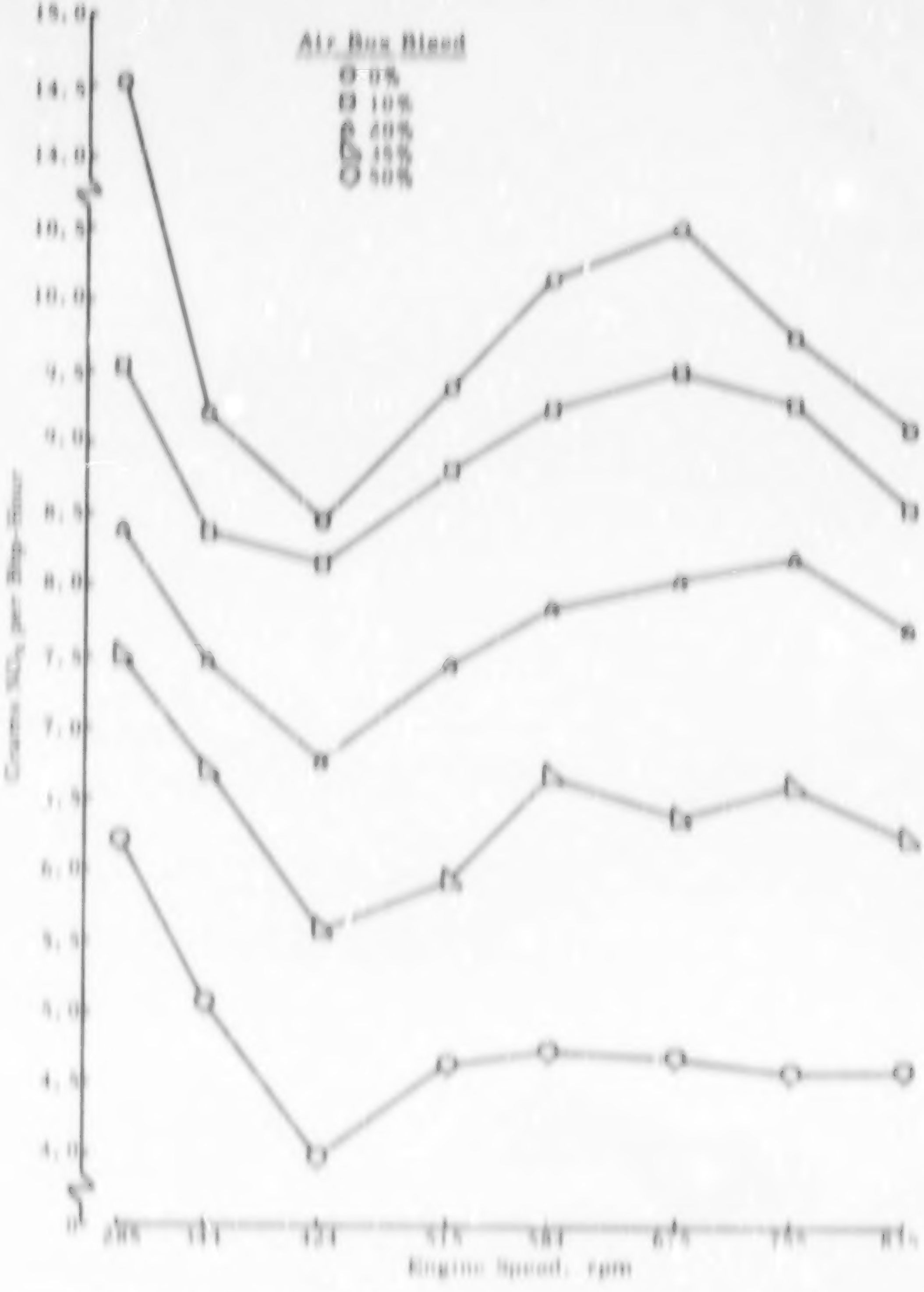

FIGURE C-47. MODAL BRAKE SPECIFIC NO$_x$ FOR VARIOUS AIR BOX BLEED RATES--NEEDLE-VALVE INJECTORS AT STANDARD TIMING

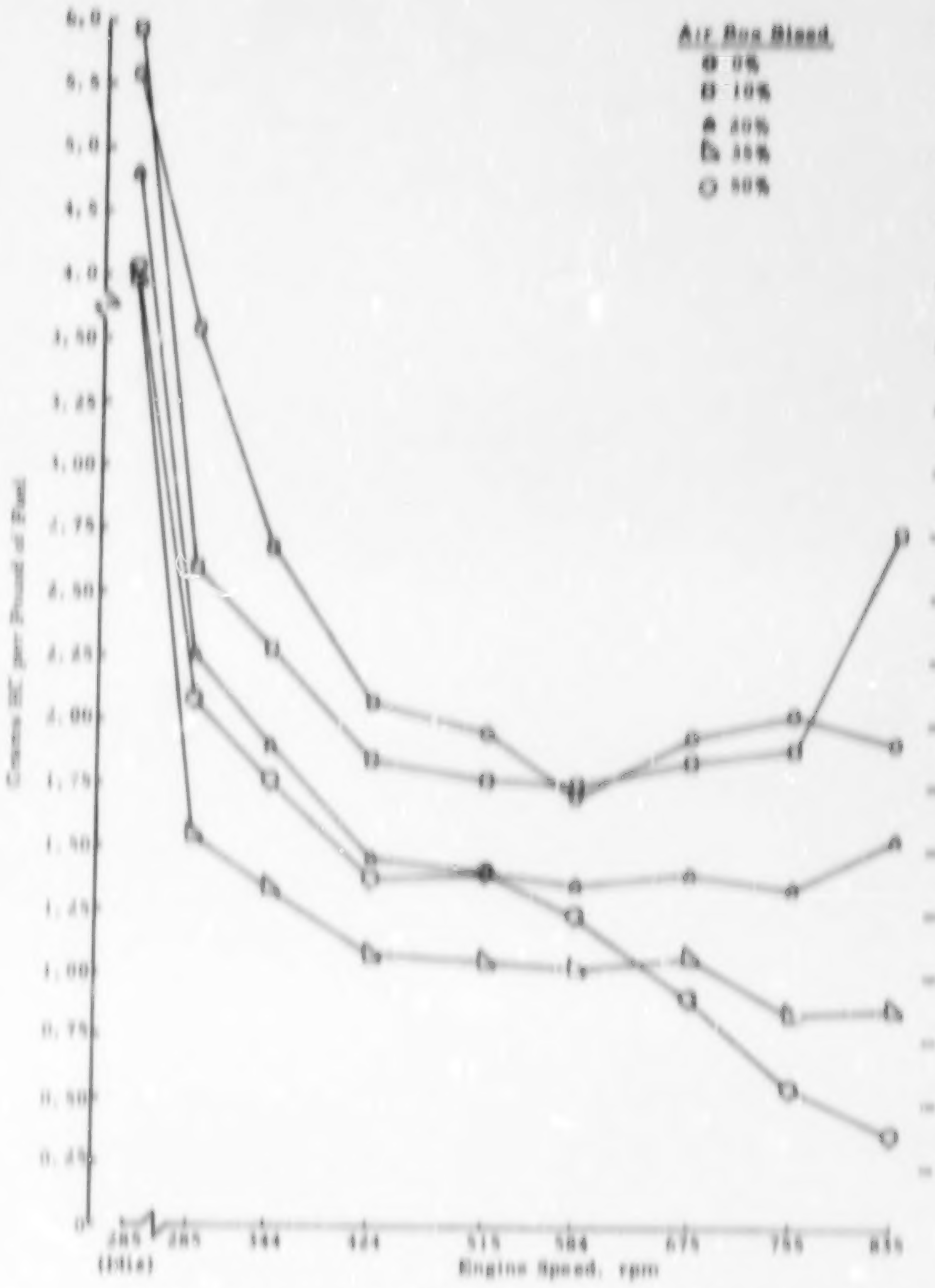

FIGURE C-48. MODAL FUEL SPECIFIC HC FOR VARIOUS AIR BOX BLEED RATES--NEEDLE-VALVE INJECTORS AT STANDARD TIMING

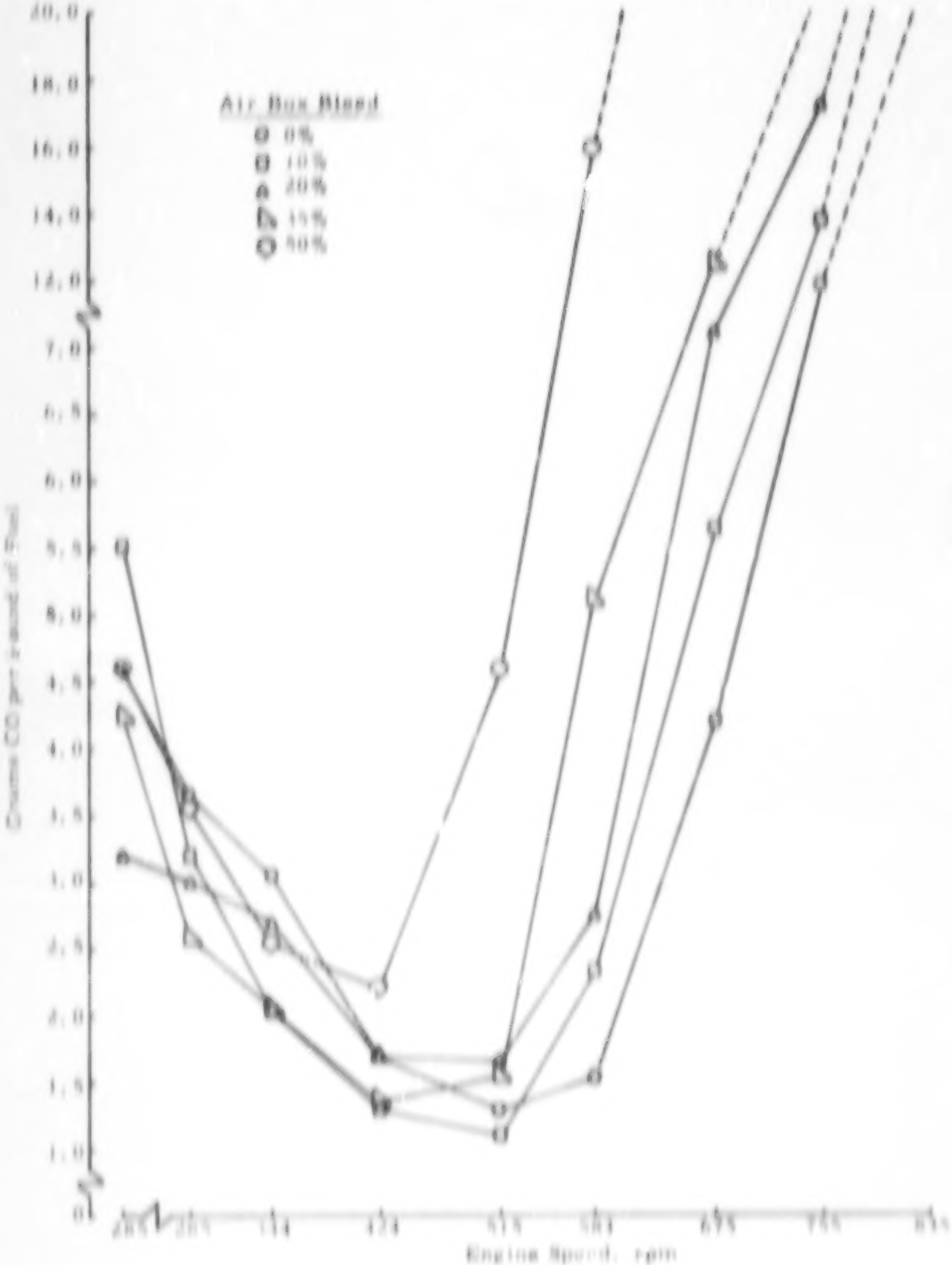

FIGURE C-49. MODAL FUEL SPECIFIC CO FOR VARIOUS AIR BOX BLEED RATES: NEEDLE-VALVE INJECTORS AT STANDARD TIMING

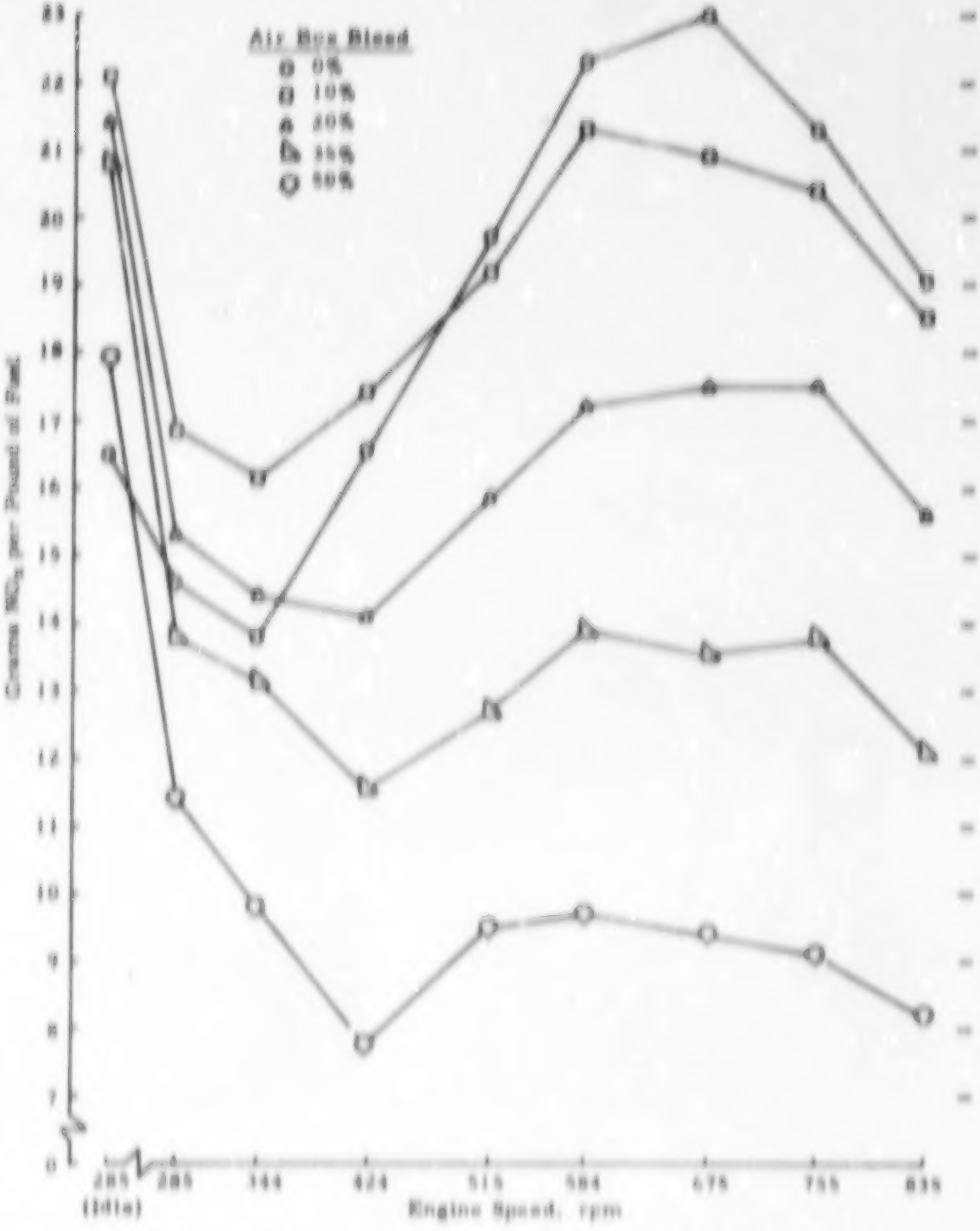

FIGURE C-50. MODAL FUEL SPECIFIC NO$_x$ FOR VARIOUS AIR BOX BLEED RATES--NEEDLE-VALVE INJECTORS AT STANDARD TIMING

TABLE C-19. MODAL BRAKE SPECIFIC AND FUEL SPECIFIC EMISSIONS FOR LOW-SAC INJECTORS, STANDARD TIMING, AND AIR BOX BLEED

Mode	Engine Speed, rpm	Grams/Bhp-Hour			Grams/Pound of Fuel		
		HC	CO	NO_x	HC	CO	NO_x
			0% Air Bleed*				
1, 6, 11	285	°	°	°	3,86	5,08	29,32
2	285	0,71	1,81	12,79	1,28	3,24	22,92
3	344	0,61	1,25	11,23	1,22	2,49	22,38
4	424	0,46	0,69	11,41	1,03	1,55	25,72
5	515	0,41	0,44	12,87	0,99	1,02	29,84
7	584	0,42	0,56	13,82	0,99	1,31	32,29
8	675	0,49	1,04	13,61	1,14	2,40	31,47
9	755	0,54	3,28	13,16	1,24	7,56	30,27
10	835	0,60	8,86	12,19	1,32	19,75	27,19
			20% Air Bleed*				
1, 6, 11	285	°	°	°	4,26	4,42	28,96
2	285	0,94	1,76	10,61	1,78	3,38	20,23
3	344	0,74	1,35	7,96	1,54	2,79	16,54
4	424	0,59	0,93	8,15	1,33	2,10	18,46
5	515	0,53	1,04	9,44	1,19	2,33	21,24
7	584	0,54	1,83	9,63	1,24	4,18	21,98
8	675	0,57	4,28	9,66	1,30	9,75	21,99
9	755	0,52	10,87	9,74	1,16	23,90	21,41
10	835	0,51	20,19	8,76	1,05	41,72	18,10
			35% Air Bleed*				
1, 6, 11	285	°	°	°	2,91	5,37	21,13
2	285	0,62	1,61	7,95	1,20	3,10	15,37
3	344	0,47	1,09	6,12	1,04	2,52	13,79
4	424	0,39	1,05	6,57	0,83	2,25	12,91
5	515	0,36	2,44	6,74	0,80	5,50	15,16
7	584	0,36	5,95	6,78	0,81	13,18	14,99
8	675	0,34	11,27	6,47	0,74	24,41	13,98
9	755	0,26	18,19	6,74	0,53	37,47	13,90
10	835	0,25	19,66	6,66	0,48	37,57	12,74

*Percent of engine air flow mass requirement per mode.

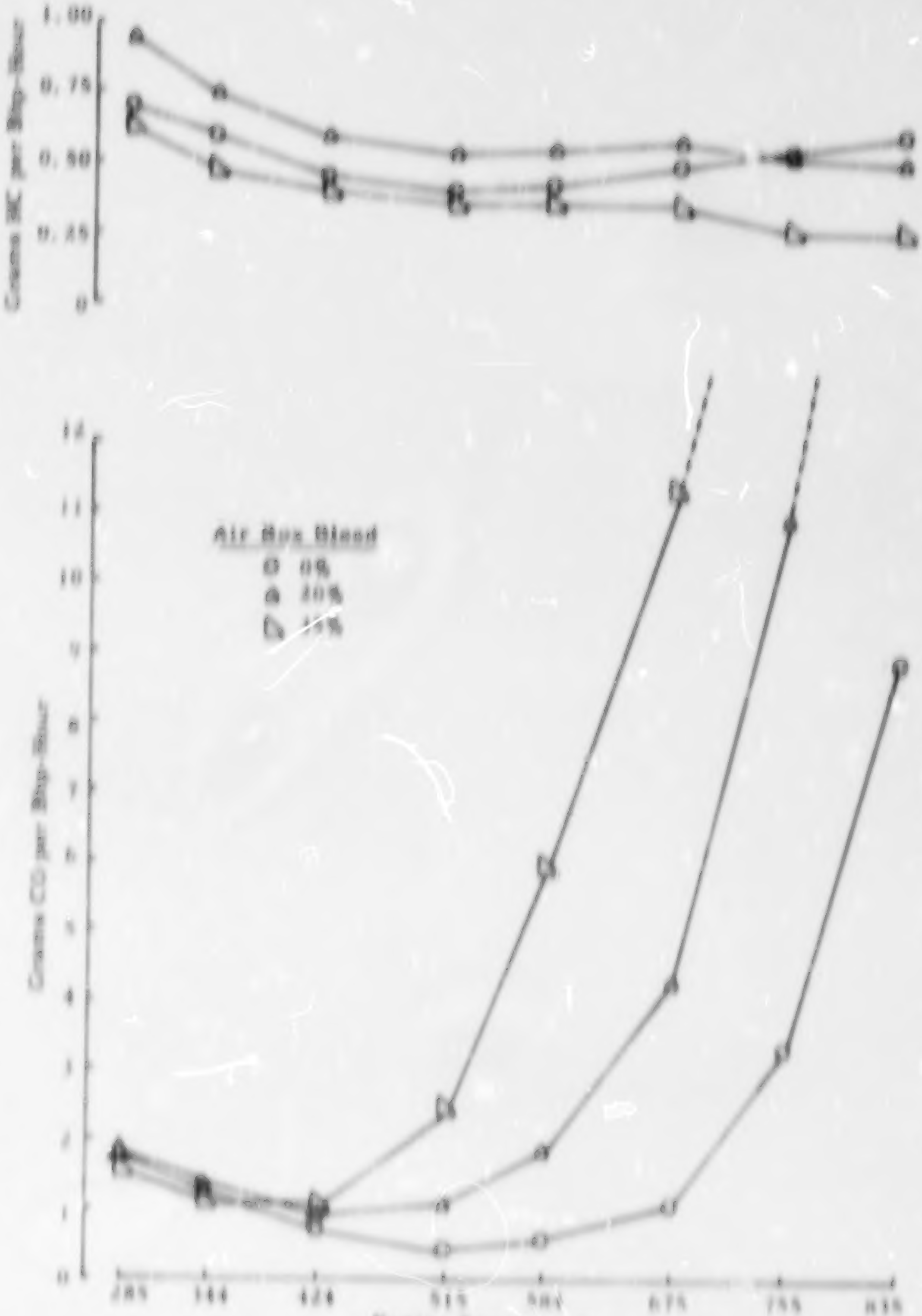

FIGURE C-31. MODAL BRAKE SPECIFIC HC AND CO FOR VARIOUS AIR BOX BLEED RATES--LOW-SAC INJECTORS AT STANDARD TIMING

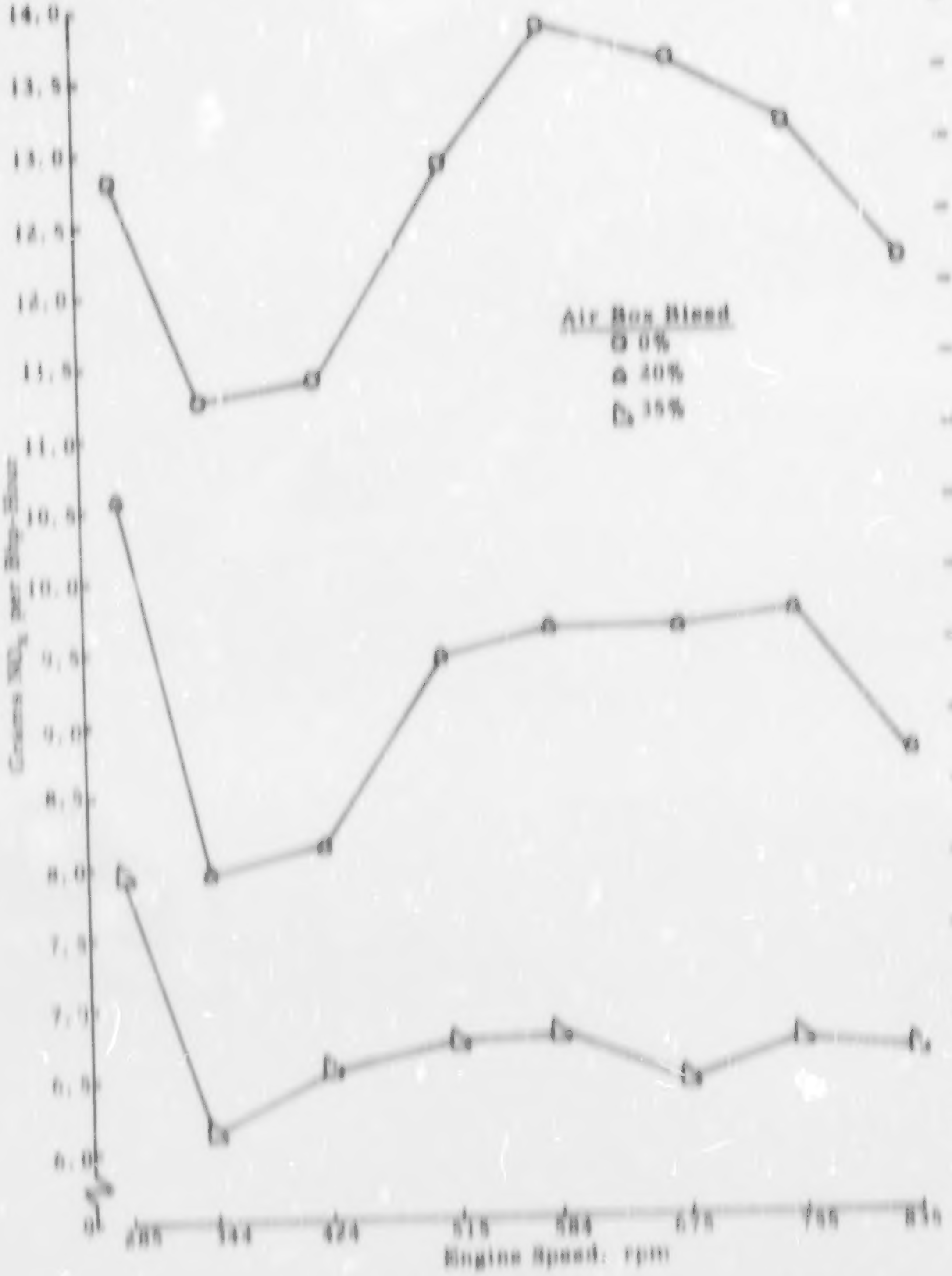

FIGURE C-52. MODAL BRAKE SPECIFIC NO_x FOR VARIOUS AIR BOX BLEED RATES--LOW-SAC INJECTORS AT STANDARD TIMING

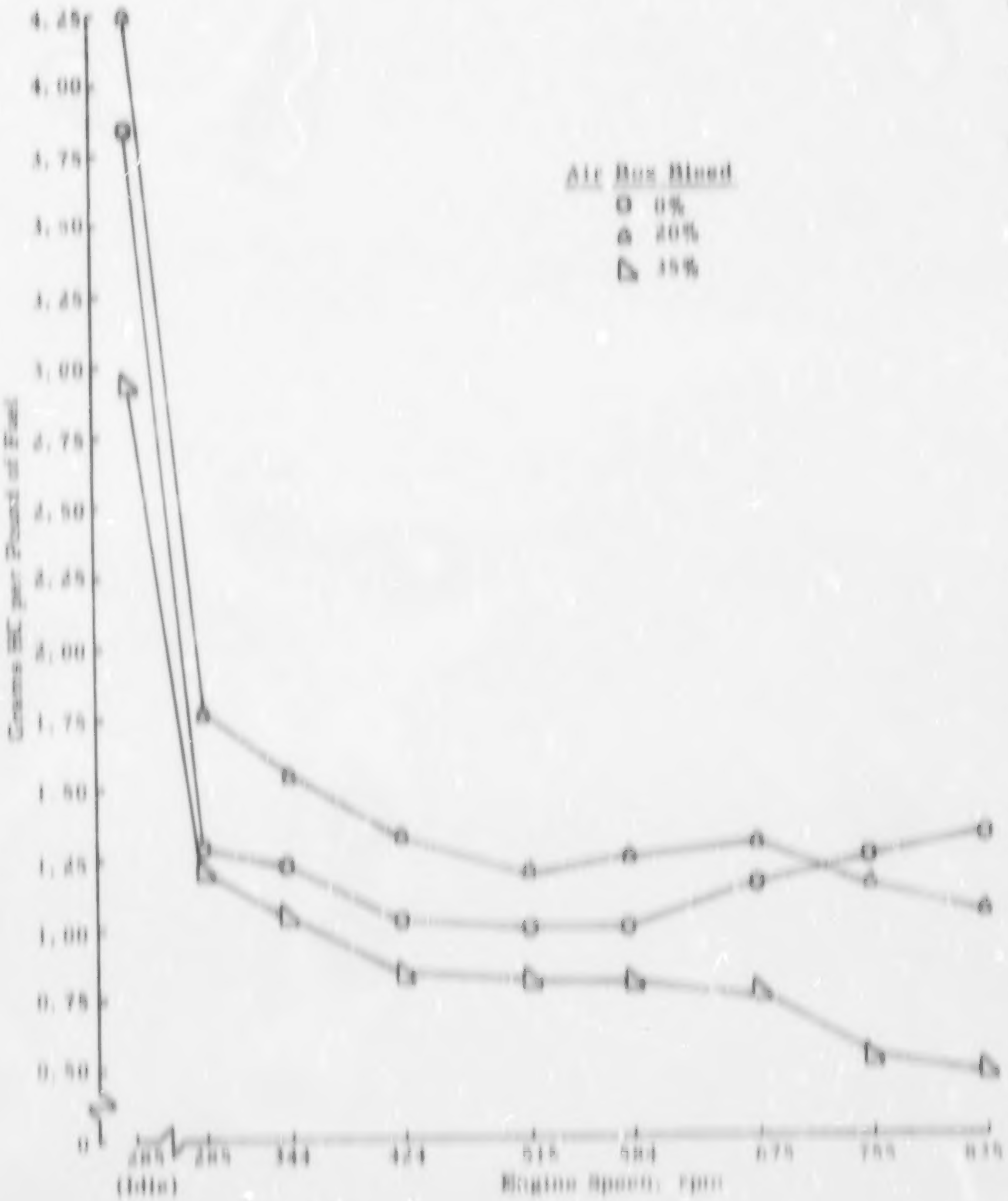

FIGURE C-51. MODAL FUEL SPECIFIC HC FOR VARIOUS AIR BOX BLEED RATES--LOW-SAC INJECTORS AT STANDARD TIMING

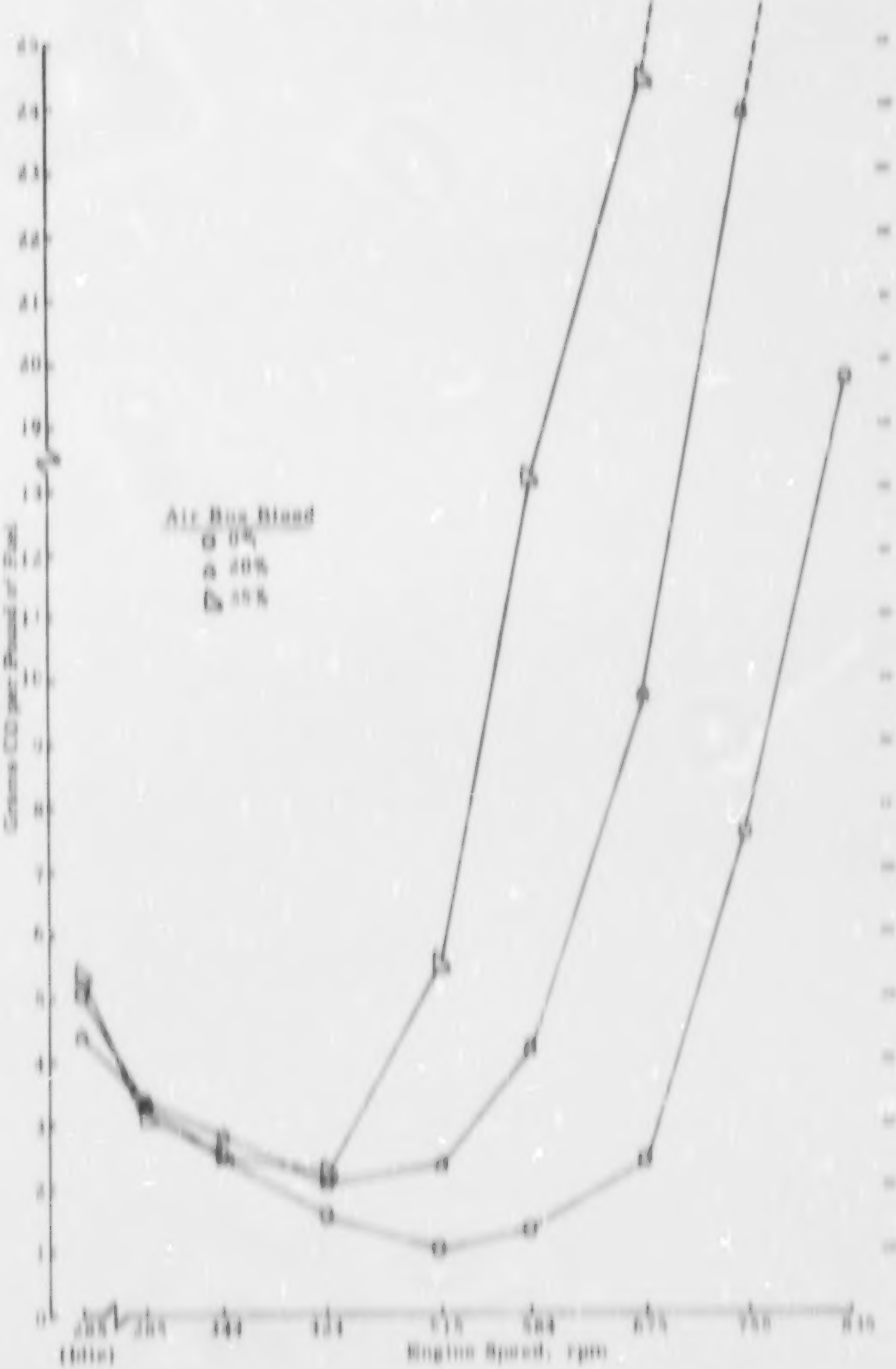

FIGURE C-51. MODAL FUEL SPECIFIC CO FOR VARIOUS AIR BOX BLEED RATES - LOW-SAC INJECTORS AT STANDARD TIMING

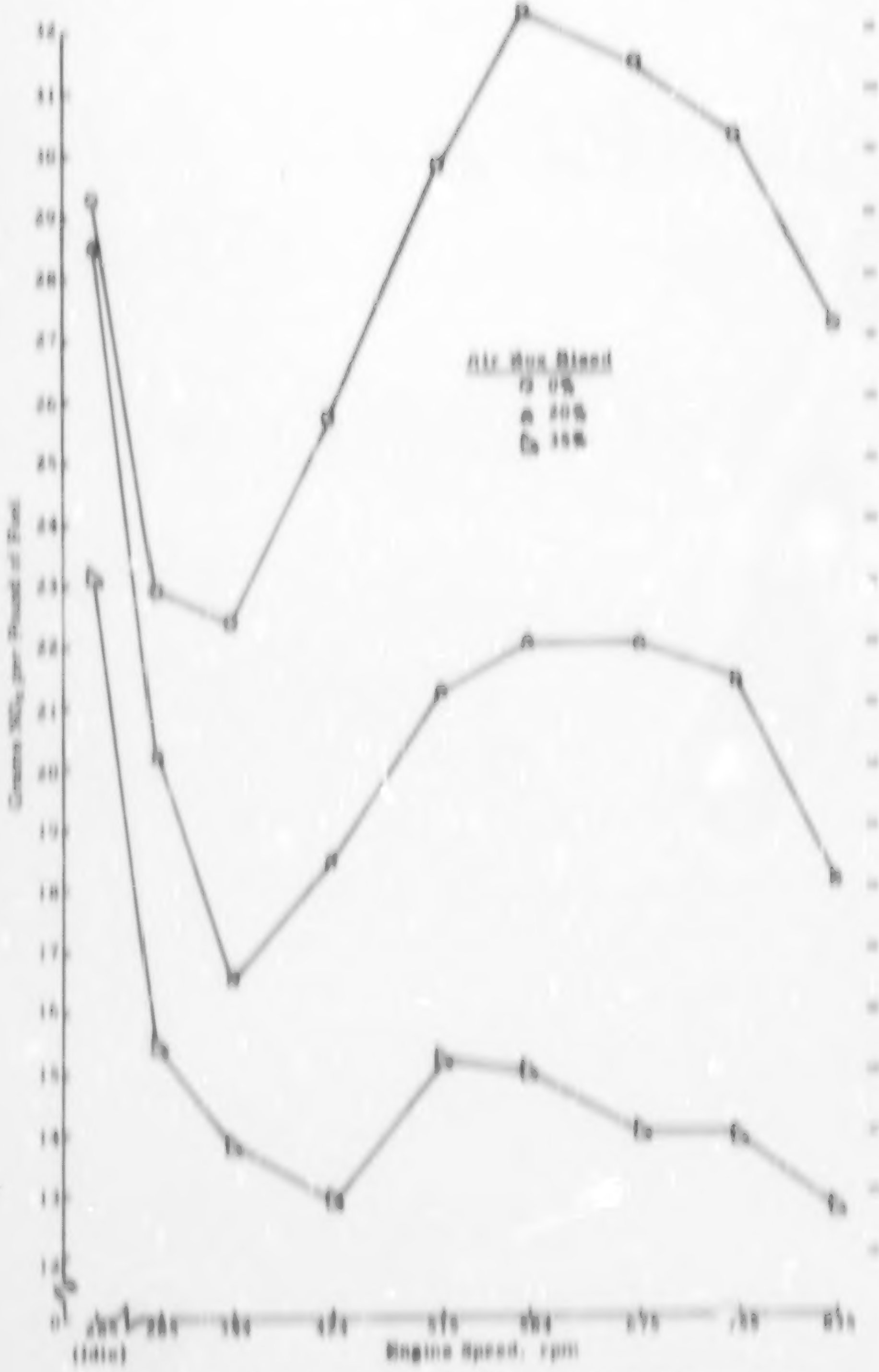

FIGURE [illegible]. MODAL FUEL SPECIFIC NO$_x$ FOR VARIOUS AIR BOX BLEED RATES: LOW-SAC INJECTORS AT STANDARD TIMING

TABLE C-11. SUMMARY OF EMISSION CONCENTRATIONS FOR VARIOUS RATES OF COOLED EGR--NEEDLE-VALVE INJECTORS AT STANDARD TIMING

Mode	Engine Speed, rpm	EGR Rates* 0%	10%	20%	30%
		HC Concentrations, ppmC			
1, 6, 11	285	142	103	104	109
2	285	128	86	86	84
3	344	139	100	102	105
4	424	154	128	122	128
5	515	176	150	146	155
7	584	184	152	168	189
8	675	232	190	218	236
9	755	272	244	274	281
10	835	288	298	334	335
		CO Concentrations, ppm			
1, 6, 11	285	59	58	44	67
2	285	66	65	65	66
3	344	77	77	64	70
4	424	63	75	52	76
5	515	58	81	69	109
7	584	82	132	177	363
8	675	252	370	622	898
9	755	800	884	1482	2344
10	835	1999	2581	4049	5283
		NO_x Concentrations, ppm			
1, 6, 11	285	128	120	121	127
2	285	162	196	191	191
3	344	219	259	233	227
4	424	375	387	352	312
5	515	540	504	429	341
7	584	733	665	512	367
8	675	842	744	528	402
9	755	870	720	486	380
10	835	874	713	457	366

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*Percent of engine air flow mass requirement per mode.

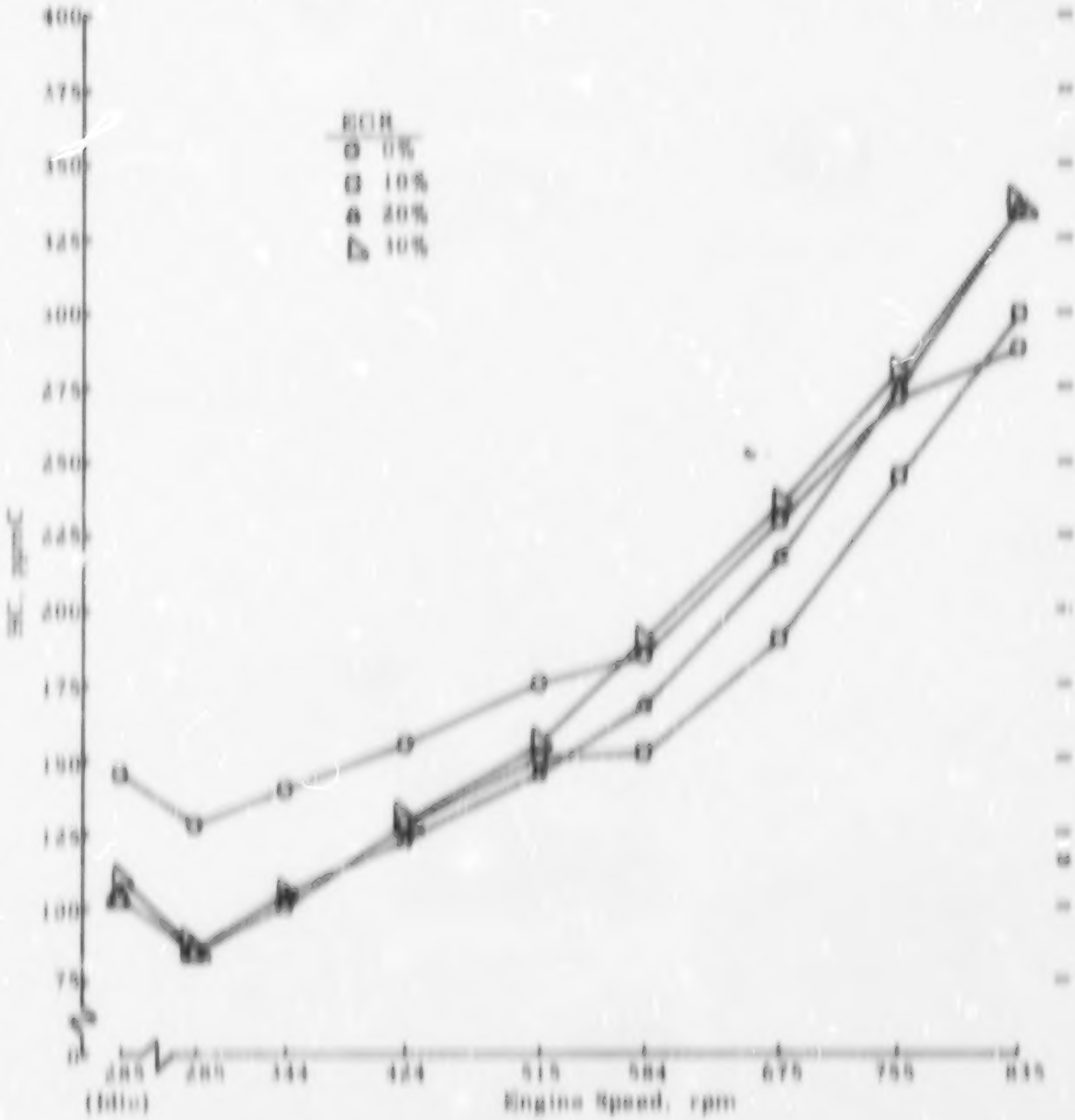

FIGURE C-56. MODAL HC CONCENTRATIONS FOR VARIOUS RATES OF COOLED EGR - NEEDLE-VALVE INJECTORS AT STANDARD TIMING

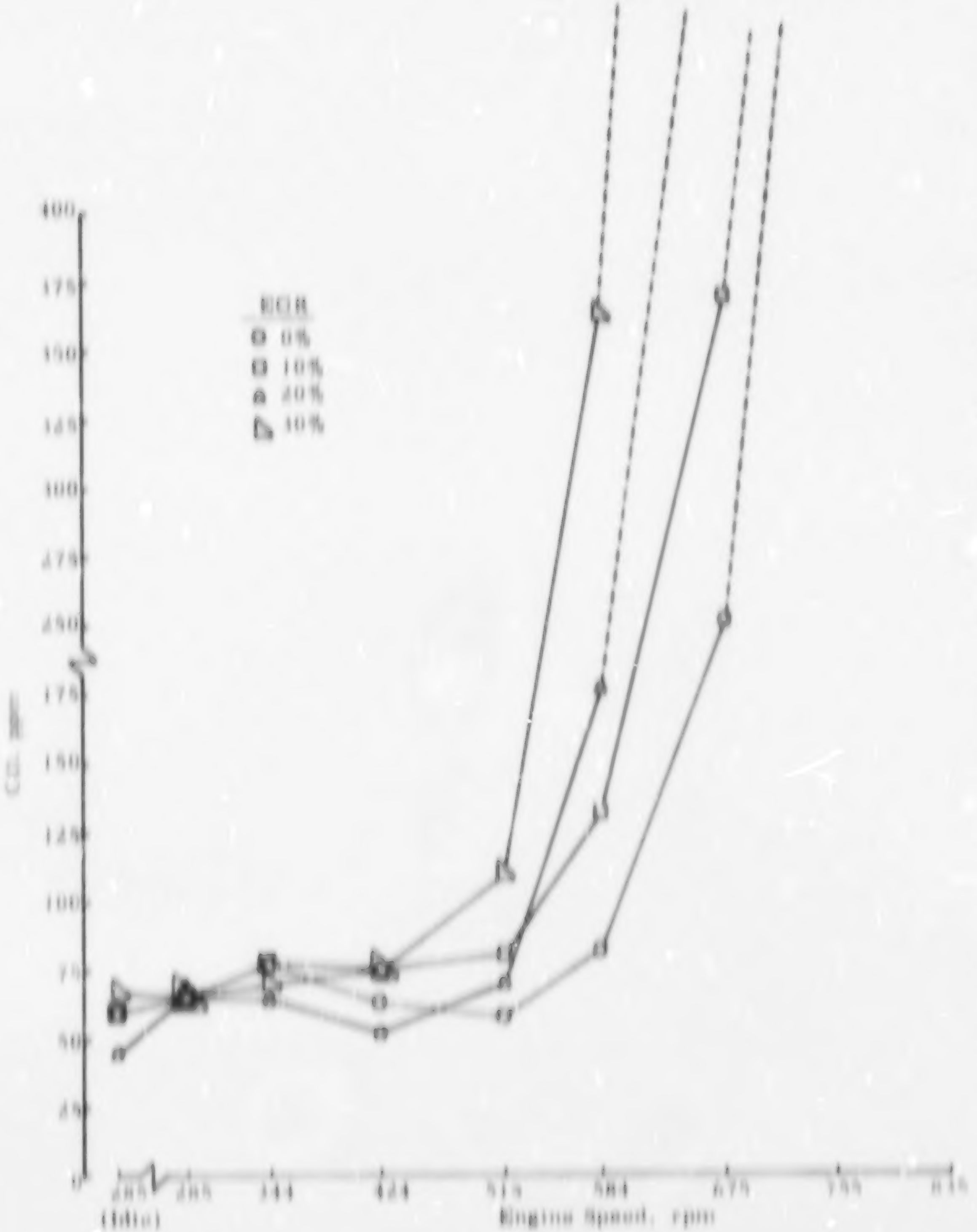

FIGURE C-37. MODAL CO CONCENTRATIONS FOR VARIOUS RATES OF COOLED EGR - NEEDLE-VALVE INJECTORS AT STANDARD TIMING

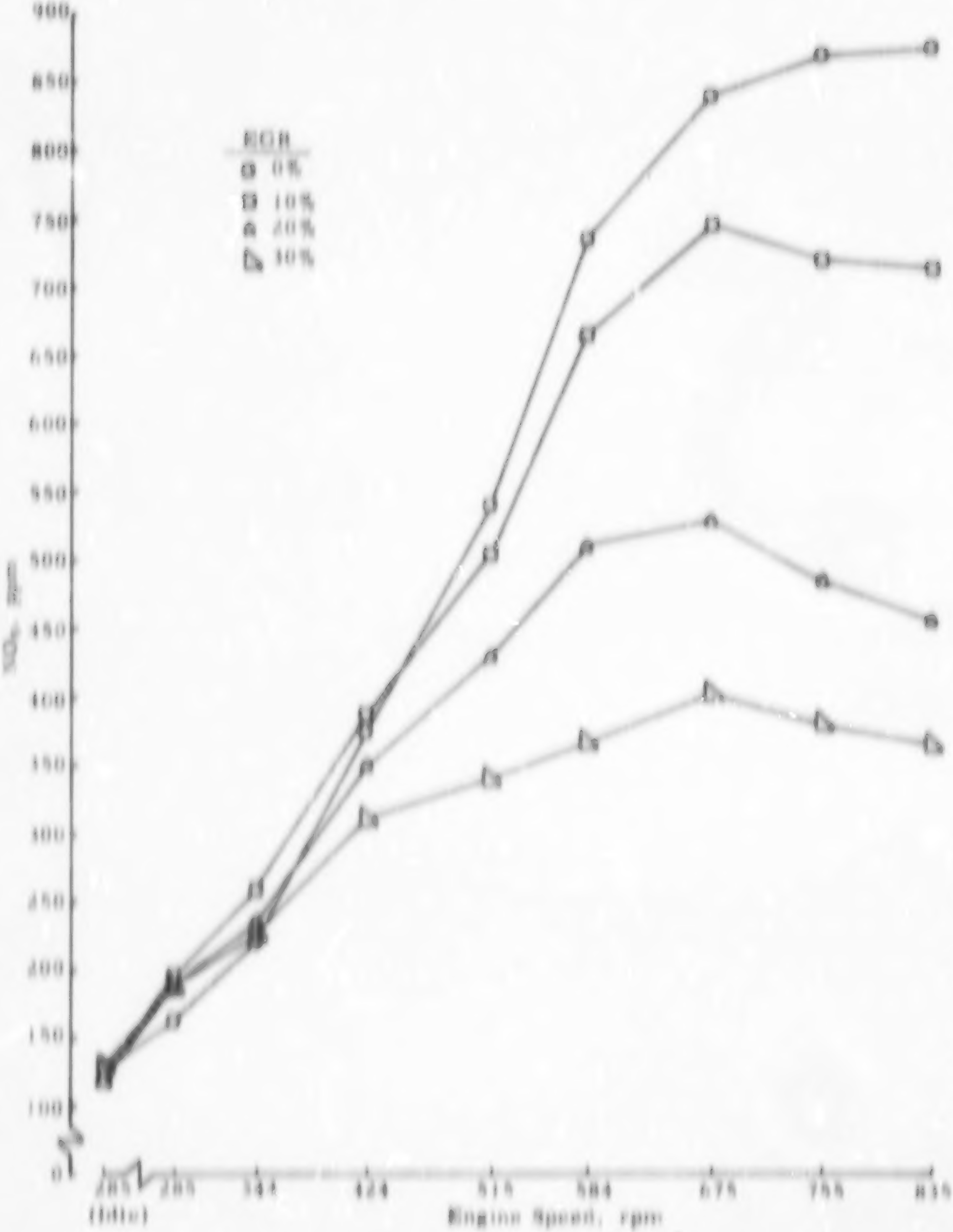

FIGURE C-58. MODAL NO_x CONCENTRATIONS FOR VARIOUS RATES OF COOLED EGR--NEEDLE-VALVE INJECTORS AT STANDARD TIMING

TABLE C-12. SUMMARY OF EMISSION CONCENTRATIONS FOR VARIOUS RATES OF COOLED EGR--LOW-SAC INJECTORS AT STANDARD TIMING

Mode	Engine Speed, rpm	Nominal EGR Rates*		
		0%	20%	30%
		HC Concentrations, ppmC		
1, 6, 11	285	68	49	69
2	285	49	43	60
3	344	61	50	65
4	424	72	50	78
5	515	81	58	83
7	584	93	75	103
8	675	125	105	135
9	755	151	153	178
10	835	181	178	190
		CO Concentrations, ppm		
1, 6, 11	285	45	52	62
2	285	63	71	89
3	344	63	82	88
4	424	54	75	75
5	515	42	69	91
7	584	65	137	222
8	675	133	351	622
9	755	459	1344	2526
10	835	1355	4013	4686
		NO_x Concentrations, ppm		
1, 6, 11	285	158	147	157
2	285	271	339	235
3	344	342	276	256
4	424	549	441	373
5	515	750	584	480
7	584	971	721	505
8	675	1058	750	565
9	755	1121	669	521
10	835	1136	593	495

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*Percent of engine air flow mass requirement per mode.

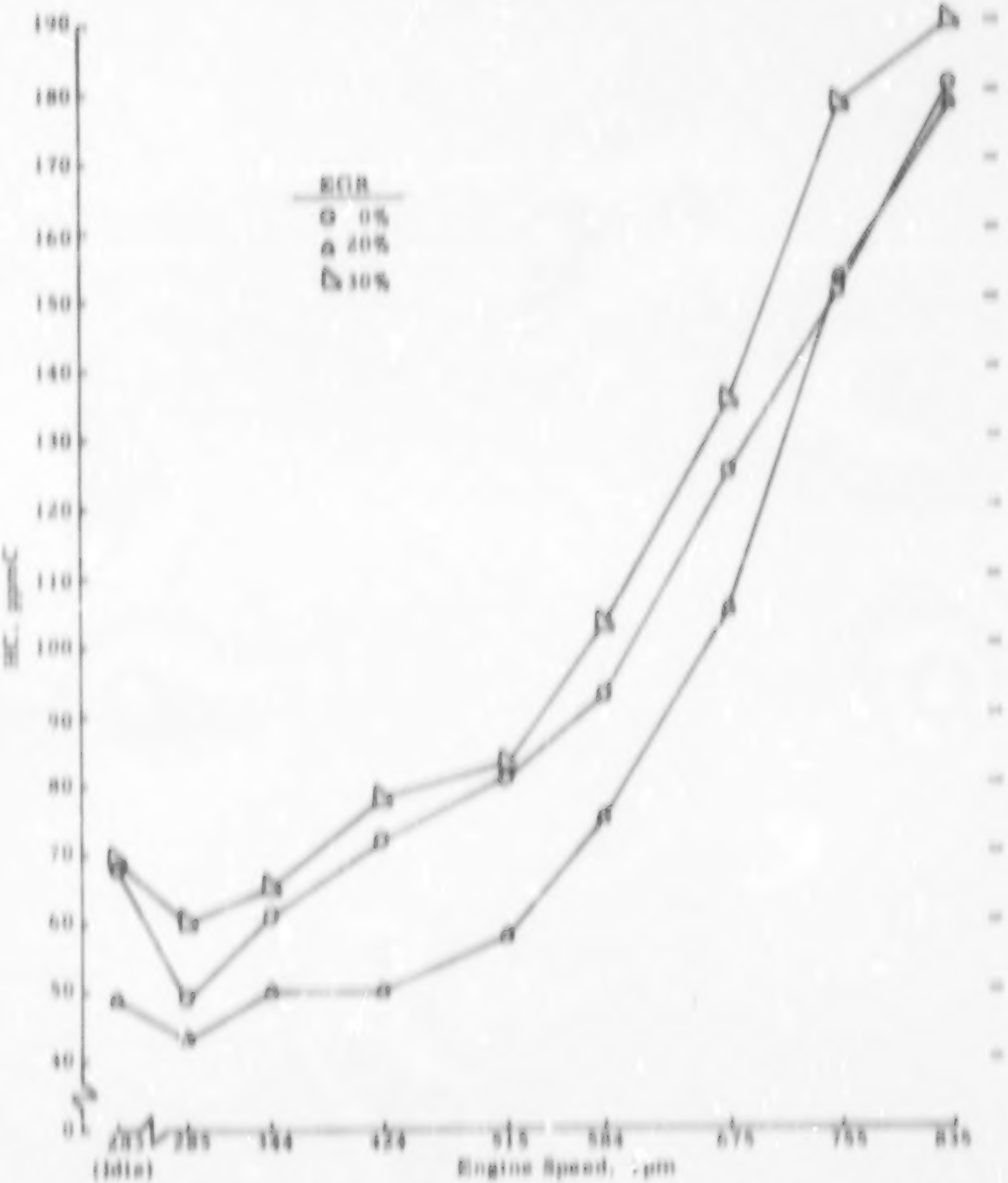

FIGURE C-59. MODAL HC CONCENTRATIONS FOR VARIOUS RATES OF COOLED EGR--LOW-SAC INJECTORS AT STANDARD TIMING

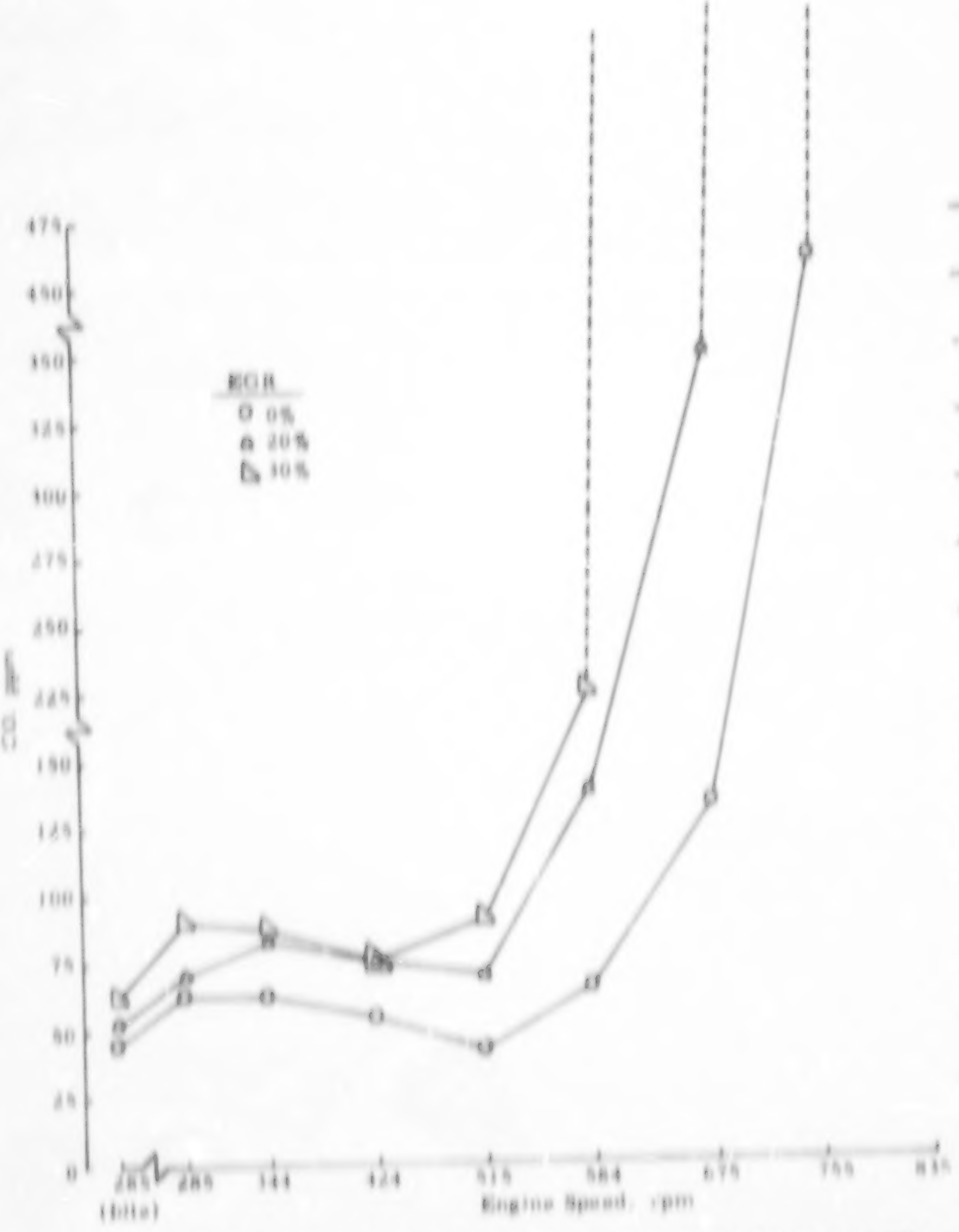

FIGURE C-60. MODAL CO CONCENTRATIONS FOR VARIOUS RATES OF COOLED EGR - LOW-SAC INJECTORS AT STANDARD TIMING

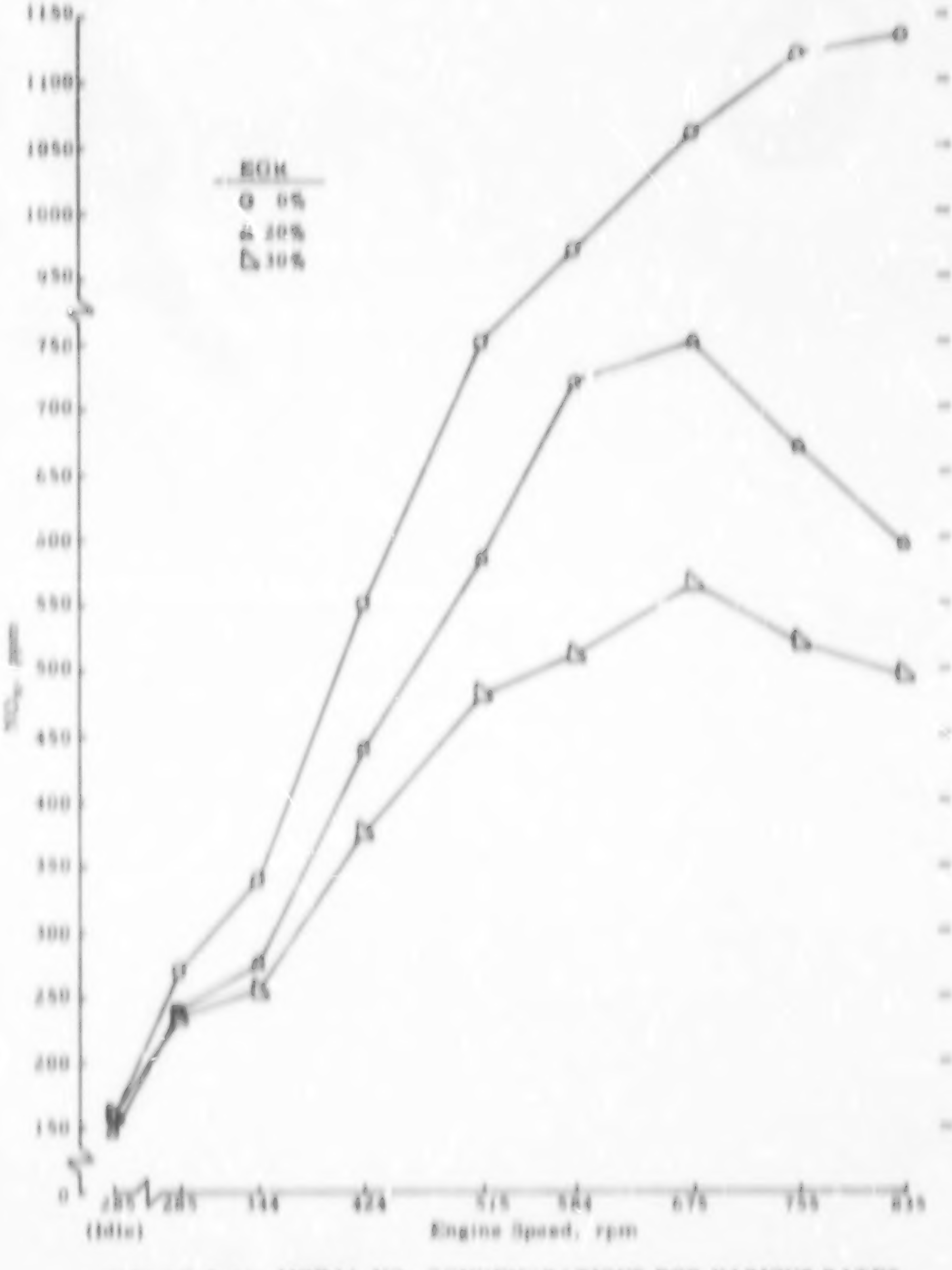

FIGURE C-61. MODAL NO$_x$ CONCENTRATIONS FOR VARIOUS RATES OF COOLED EGR—LOW SAC INJECTORS AT STANDARD TIMING

TABLE E-11. MODAL BRAKE SPECIFIC AND FUEL SPECIFIC EMISSIONS FOR NEEDLE VALVE INJECTORS, STANDARD TIMING, AND COOLED EGR

Mode	Engine Speed, rpm	Grams/Bhp-Hour HC	Grams/Bhp-Hour CO	Grams/Bhp-Hour NO_x	Grams/Pound of Fuel HC	Grams/Pound of Fuel CO	Grams/Pound of Fuel NO_x
			0% Cool EGR*				
1,6,11	285	-	-	-	4.60	6.20	16.52
2	285	1.51	1.70	14.55	3.54	3.65	18.61
3	364	1.80	2.06	9.22	2.68	3.05	14.79
4	424	1.06	0.85	8.47	2.07	1.68	16.56
5	515	0.94	0.61	9.61	1.90	1.28	19.69
7	584	0.81	0.70	10.17	1.74	1.53	22.27
8	675	0.89	1.92	10.52	1.94	4.20	23.00
9	755	0.93	5.66	9.75	2.03	11.89	21.28
10	835	0.92	12.73	9.14	1.92	26.55	19.06
			10% Cool EGR*				
1,6,11	285	-	-	-	6.04	5.11	22.44
2	285	1.11	1.66	8.27	2.09	3.14	15.57
3	364	0.90	1.36	7.59	1.81	2.73	15.28
4	424	0.71	0.85	7.00	1.59	1.86	15.74
5	515	0.71	0.76	7.76	1.59	1.70	17.40
7	584	0.60	1.02	8.49	1.35	2.32	19.34
8	675	0.66	2.55	8.42	1.50	5.81	19.19
9	755	0.77	5.55	7.42	1.73	12.45	16.66
10	835	0.86	14.86	6.74	1.87	32.20	14.61
			20% Cool EGR*				
1,6,11	285	-	-	-	5.16	4.10	19.10
2	285	0.97	1.45	7.02	1.78	2.63	12.96
3	364	0.83	1.04	6.20	1.62	2.03	12.13
4	424	0.59	0.51	5.58	1.32	1.2[illegible]	12.40
5	515	0.61	0.57	5.84	1.39	1.30	13.34
7	584	0.55	1.23	5.86	1.36	2.84	13.49
8	675	0.67	3.81	5.31	1.54	8.71	12.18
9	755	0.78	8.37	5.52	1.73	18.65	10.05
10	835	0.91	21.87	4.06	1.91	46.14	8.56
			30% Cool EGR*				
1,6,11	285	-	-	-	4.51	3.83	18.59
2	285	0.89	1.42	6.70	1.67	2.62	12.36
3	364	0.77	1.02	5.45	1.52	2.01	10.76
4	424	0.59	0.69	4.67	1.28	1.52	10.22
5	515	0.54	0.77	3.53	1.21	1.71	8.77
7	584	0.57	2.17	3.61	1.23	4.52	9.20
8	675	0.65	4.95	3.59	1.35	11.11	8.17
9	755	0.76	12.69	3.37	1.65	27.40	7.30
10	835	0.83	16.09	2.96	1.69	5[illegible].14	6.05

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*Percent of air flow mass requirement per mode.

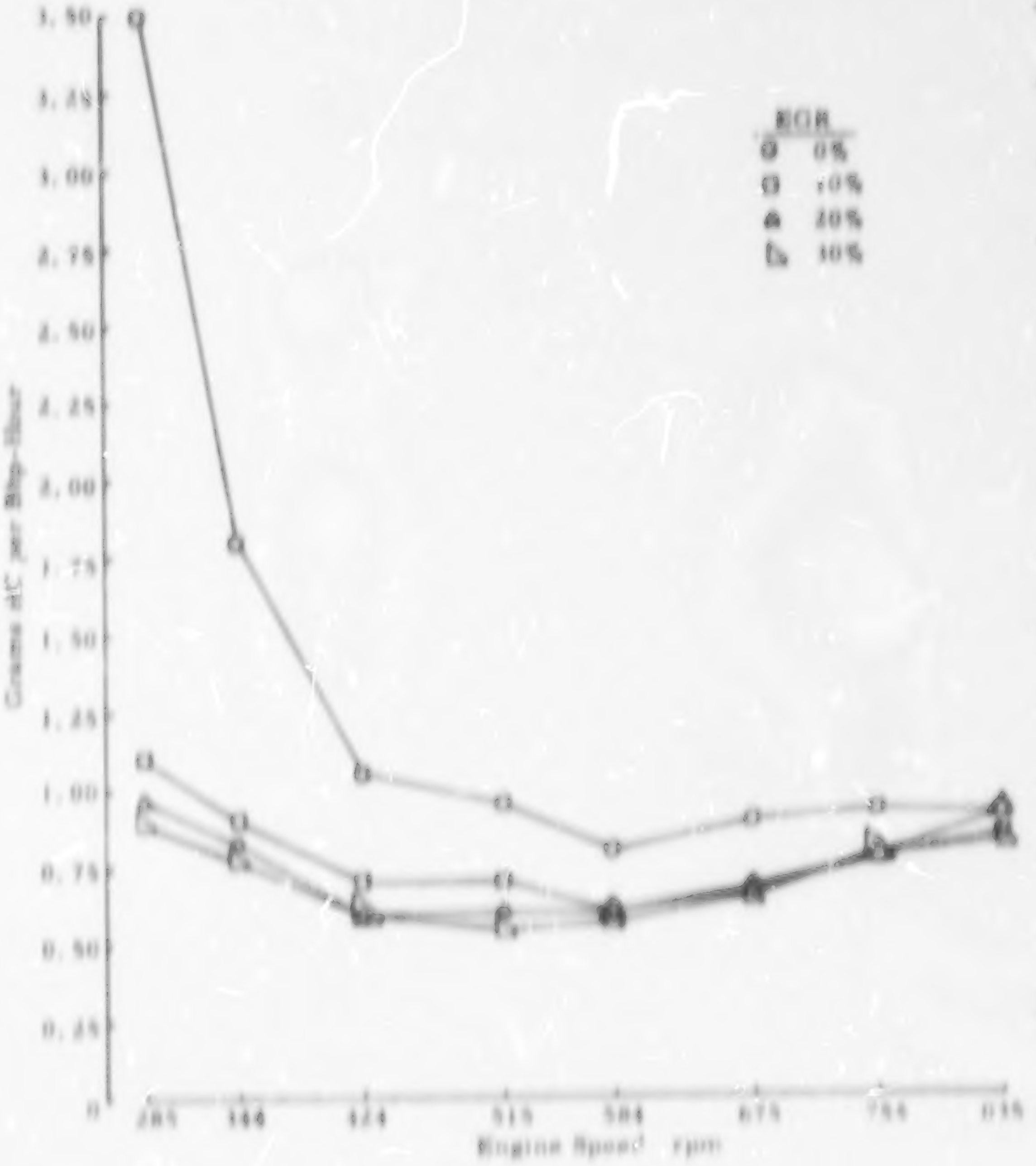

FIGURE C-62. MODAL BRAKE SPECIFIC HC FOR VARIOUS RATES OF COOLED EGR--NEEDLE-VALVE INJECTORS AT STANDARD TIMING

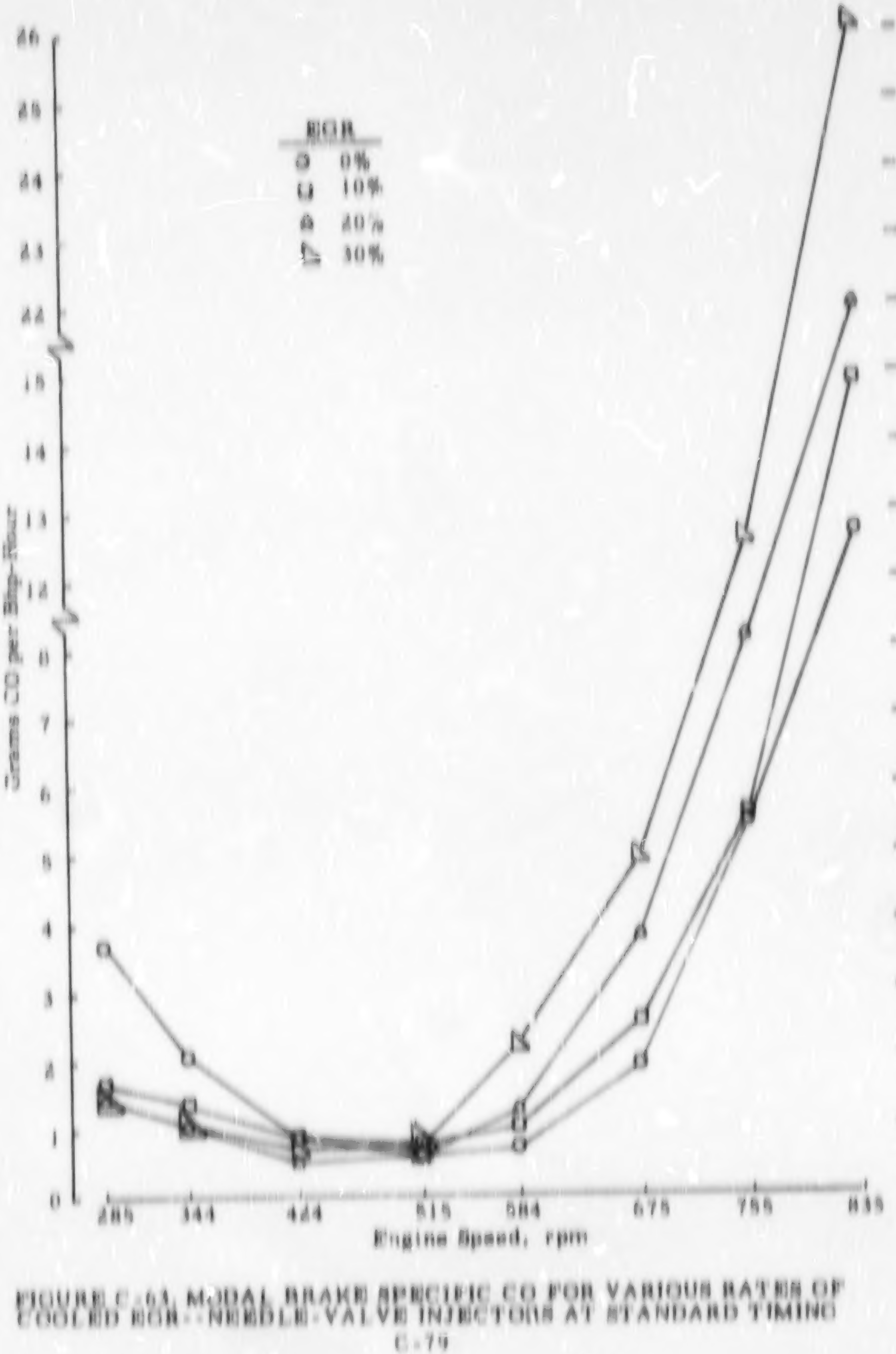

FIGURE C-63. MODAL BRAKE SPECIFIC CO FOR VARIOUS RATES OF COOLED EGR--NEEDLE-VALVE INJECTORS AT STANDARD TIMING

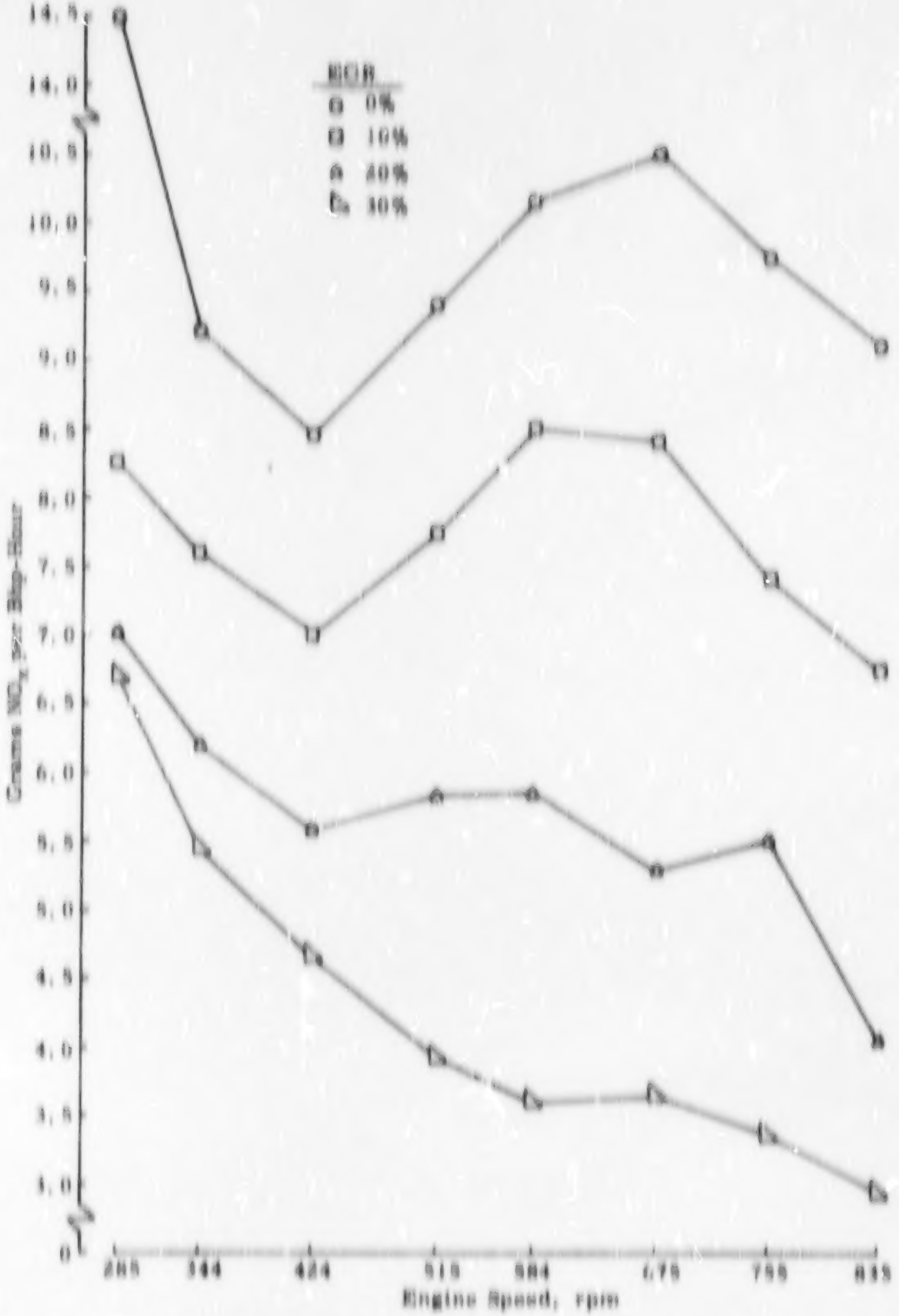

FIGURE C-64. MODAL BRAKE SPECIFIC NO_2 FOR VARIOUS RATES OF COOLED EGR--NEEDLE-VALVE INJECTORS AT STANDARD TIMING

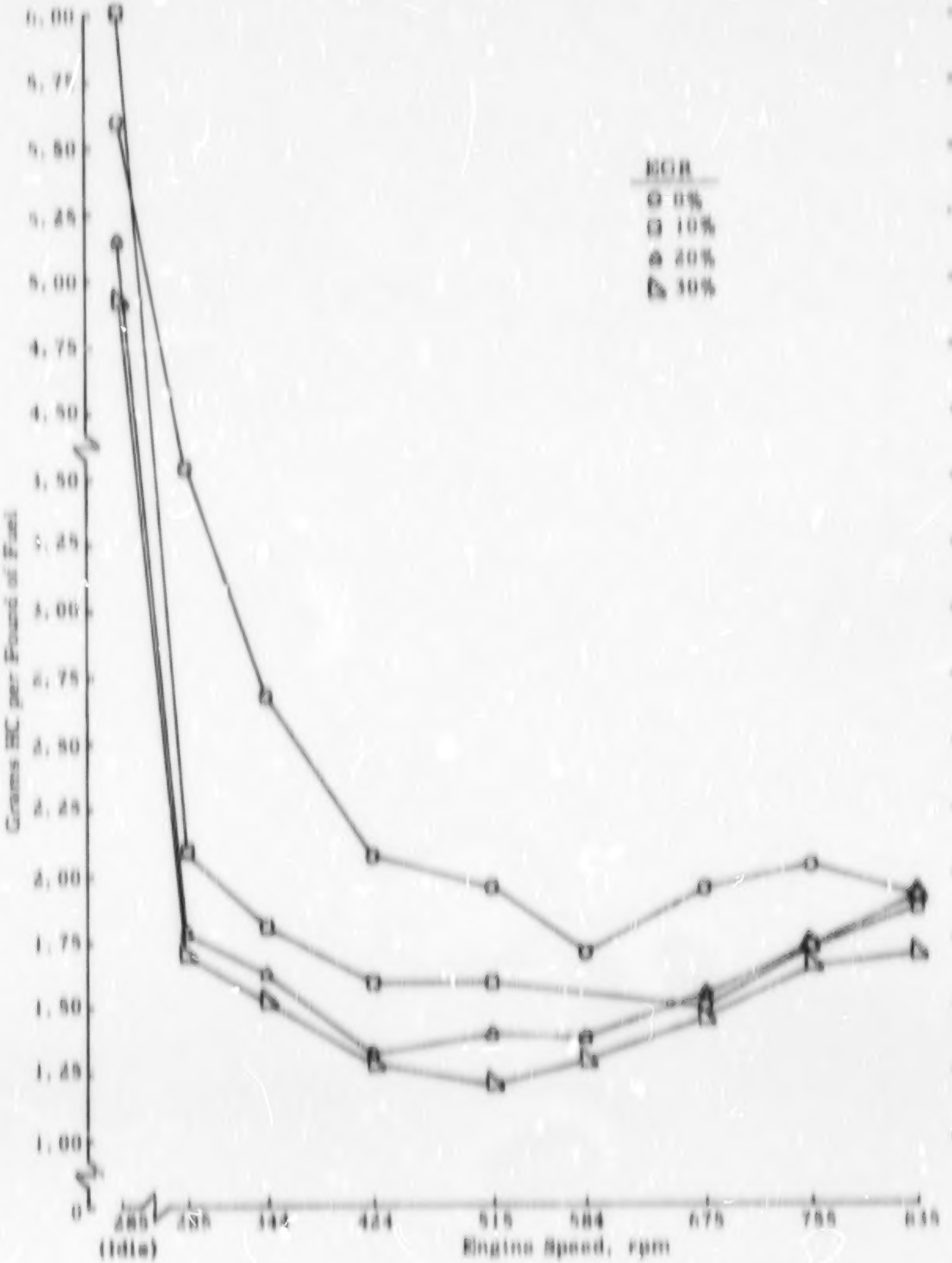

FIGURE C-65. MODAL FUEL SPECIFIC HC FOR VARIOUS RATES OF COOLED EGR--NEEDLE-VALVE INJECTORS AT STANDARD TIMING

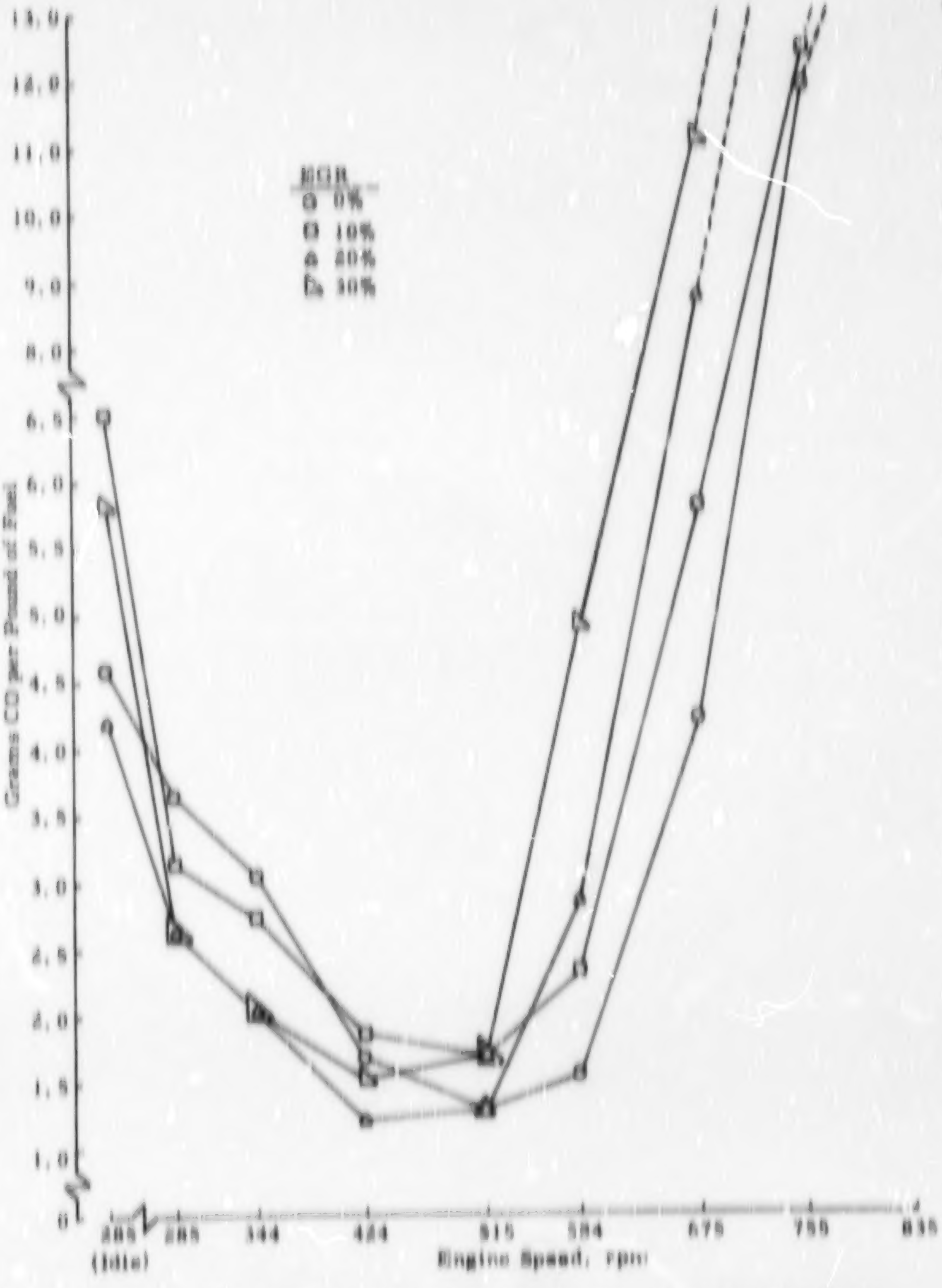

FIGURE C-60. MODAL FUEL SPECIFIC CO FOR VARIOUS RATES OF COOLED EGR--NEEDLE-VALVE INJECTORS AT STANDARD TIMING

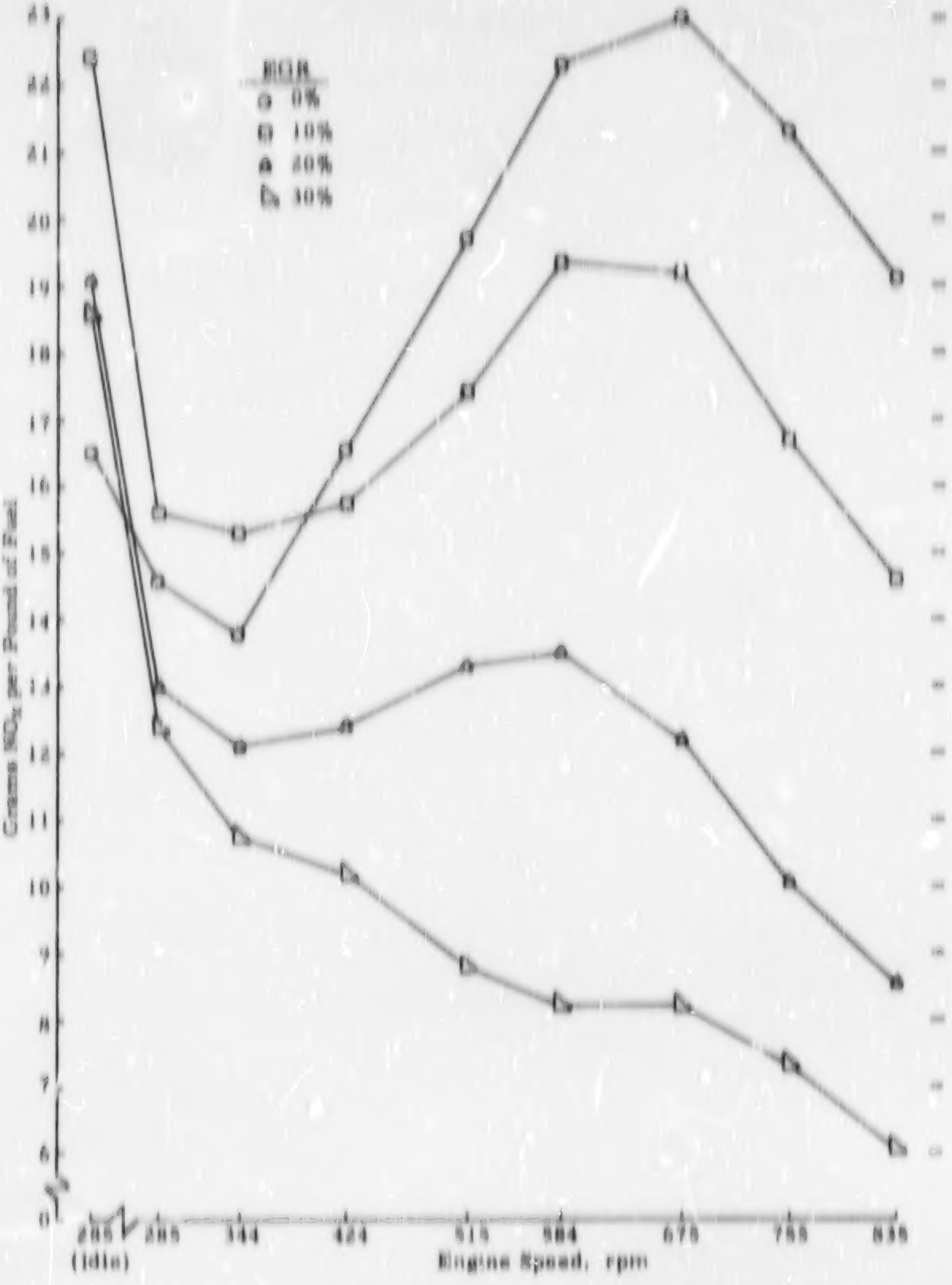

FIGURE C-67. MODAL FUEL SPECIFIC NO_x FOR VARIOUS RATES OF COOLED EGR--NEEDLE-VALVE INJECTORS AT STANDARD TIMING

TABLE C-14. MODAL BRAKE SPECIFIC AND FUEL SPECIFIC EMISSIONS FOR LOW-SAC INJECTORS, STANDARD TIMING, AND COOLED EGR

Mode	Engine Speed, rpm	Grams/Bhp-Hour HC	Grams/Bhp-Hour CO	Grams/Bhp-Hour NO_x	Grams/Pound of Fuel HC	Grams/Pound of Fuel CO	Grams/Pound of Fuel NO_x
				0% Cool EGR*			
1, 6, 11	285	-	-	-	3.86	9.08	29.32
2	285	0.71	1.81	12.79	1.28	3.24	22.92
3	344	0.61	1.75	11.23	1.22	2.49	22.38
4	424	0.46	0.69	11.41	1.03	1.55	25.72
5	515	0.41	0.44	12.87	0.99	1.02	29.84
7	584	0.42	0.56	13.82	0.99	1.31	32.29
8	675	0.49	1.04	13.61	1.14	2.40	31.47
9	755	0.54	3.28	13.16	1.24	7.56	30.27
10	835	0.60	8.86	12.19	1.32	19.75	27.19
				20% Cool EGR*			
1, 6, 11	285	-	-	-	2.99	6.10	28.02
2	285	0.51	1.68	9.17	0.99	3.29	18.24
3	344	0.41	1.33	7.36	0.88	2.86	15.83
4	424	0.26	0.78	7.48	0.61	1.83	17.60
5	515	0.25	0.58	8.10	0.59	1.40	19.42
7	584	0.27	0.99	8.57	0.65	2.35	20.36
8	675	0.33	2.22	7.78	0.80	5.28	18.53
9	755	0.46	9.31	6.62	1.06	21.44	15.25
10	835	0.49	22.23	5.40	1.09	48.89	11.87
				30% Cool EGR*			
1, 6, 11	285	-	-	-	3.55	6.20	26.08
2	285	0.56	1.98	8.41	1.26	3.72	16.19
3	344	0.48	1.30	6.14	1.01	2.73	13.02
4	424	0.36	0.65	5.60	0.84	1.61	13.14
5	515	0.31	0.69	5.93	0.76	1.66	14.35
7	584	0.34	1.44	5.44	0.80	3.43	12.88
8	675	0.40	3.62	5.40	0.93	8.55	12.75
9	755	0.50	13.70	4.64	1.13	31.42	10.64
10	835	0.49	23.76	4.13	1.04	51.54	8.95

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*Percent of engine air flow mass requirement per mode.

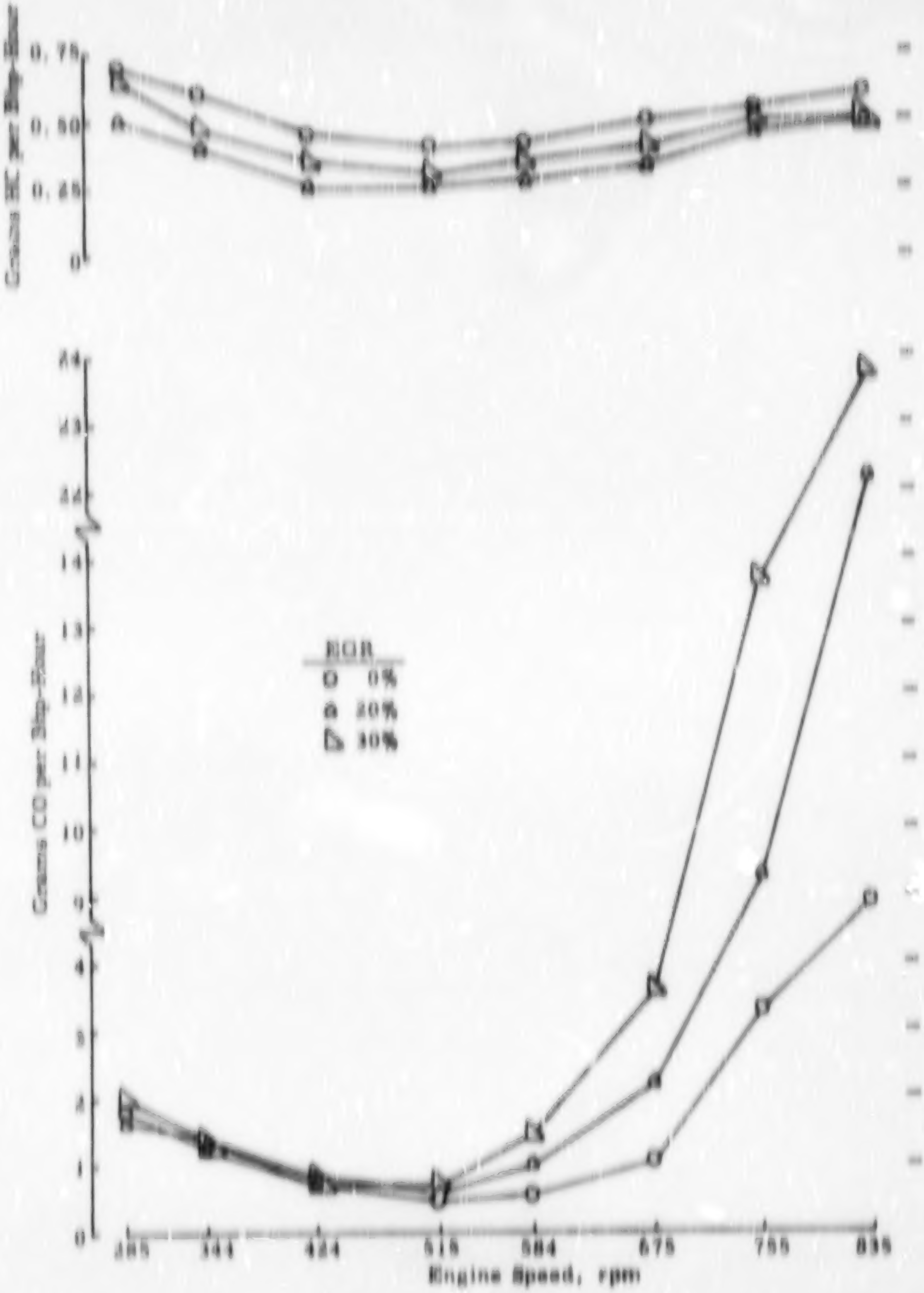

FIGURE C-68. MODAL BRAKE SPECIFIC HC AND CO FOR VARIOUS RATES OF COOLED EGR--LOW-SAC INJECTORS AT STANDARD TIMING

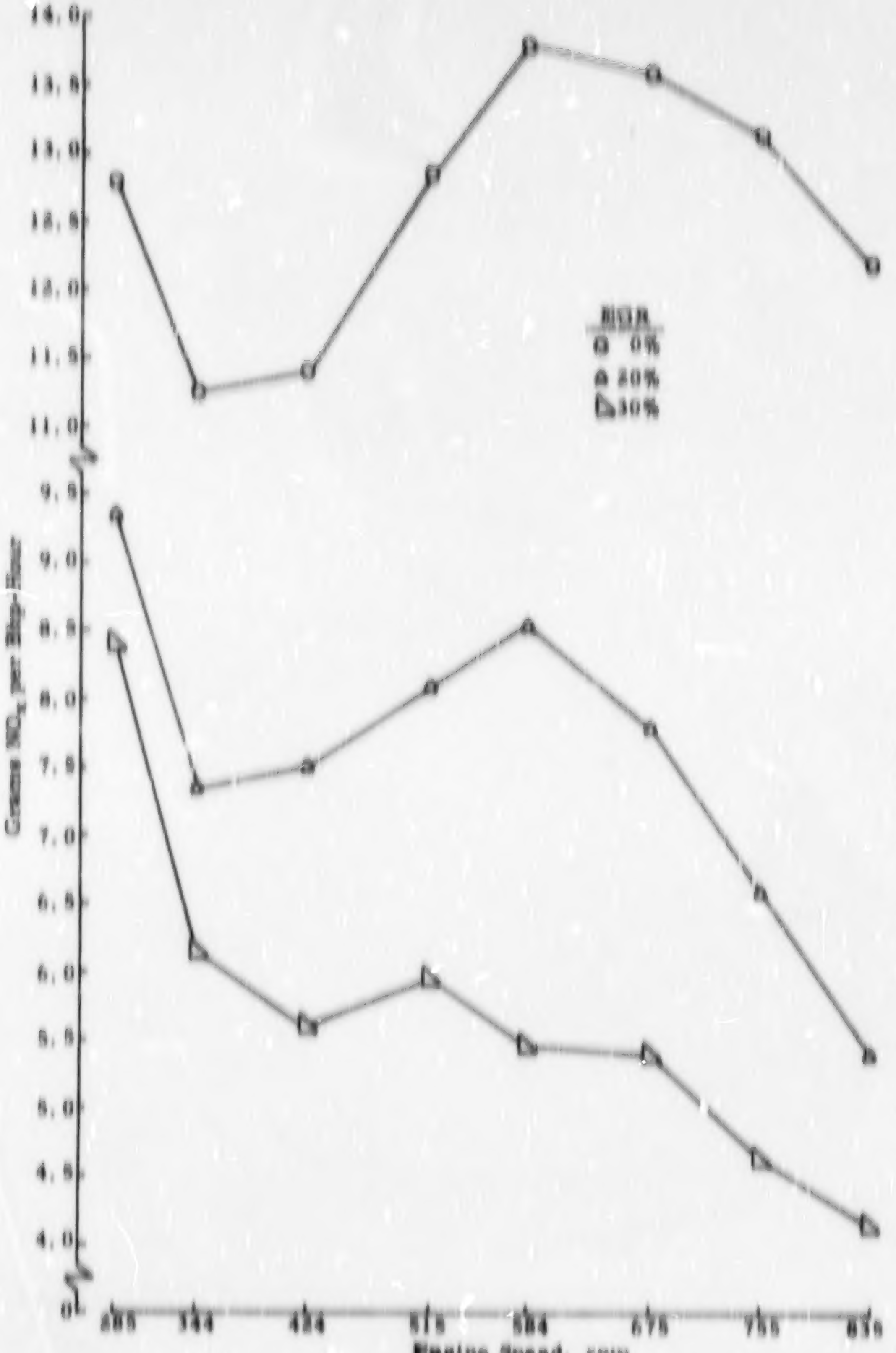

FIGURE C-69. MODAL BRAKE SPECIFIC NO_x FOR VARIOUS RATES OF COOLED EGR--LOW-SAC INJECTORS AT STANDARD TIMING

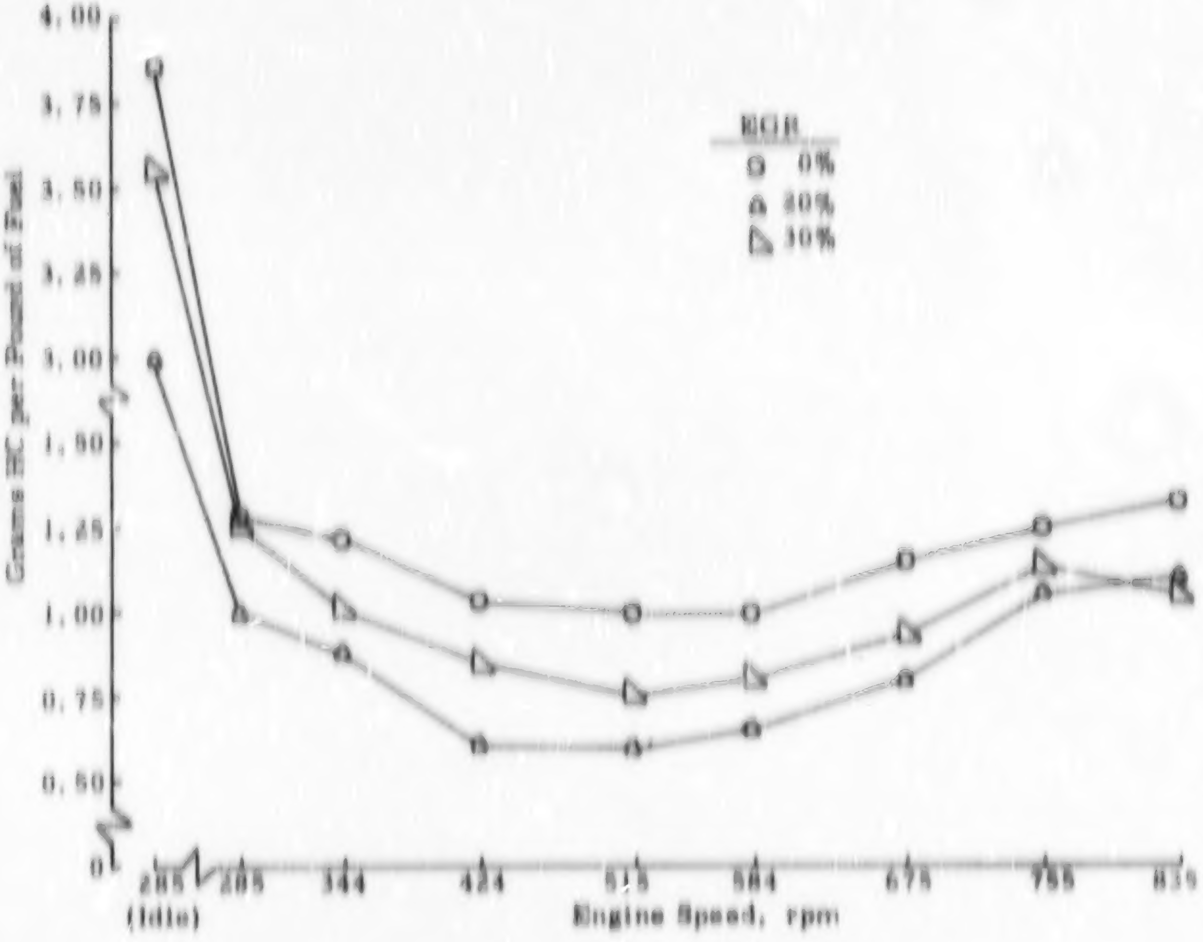

FIGURE C-70. MODAL FUEL SPECIFIC HC FOR VARIOUS RATES OF COOLED EGR--LOW-SAC INJECTORS AT STANDARD TIMING

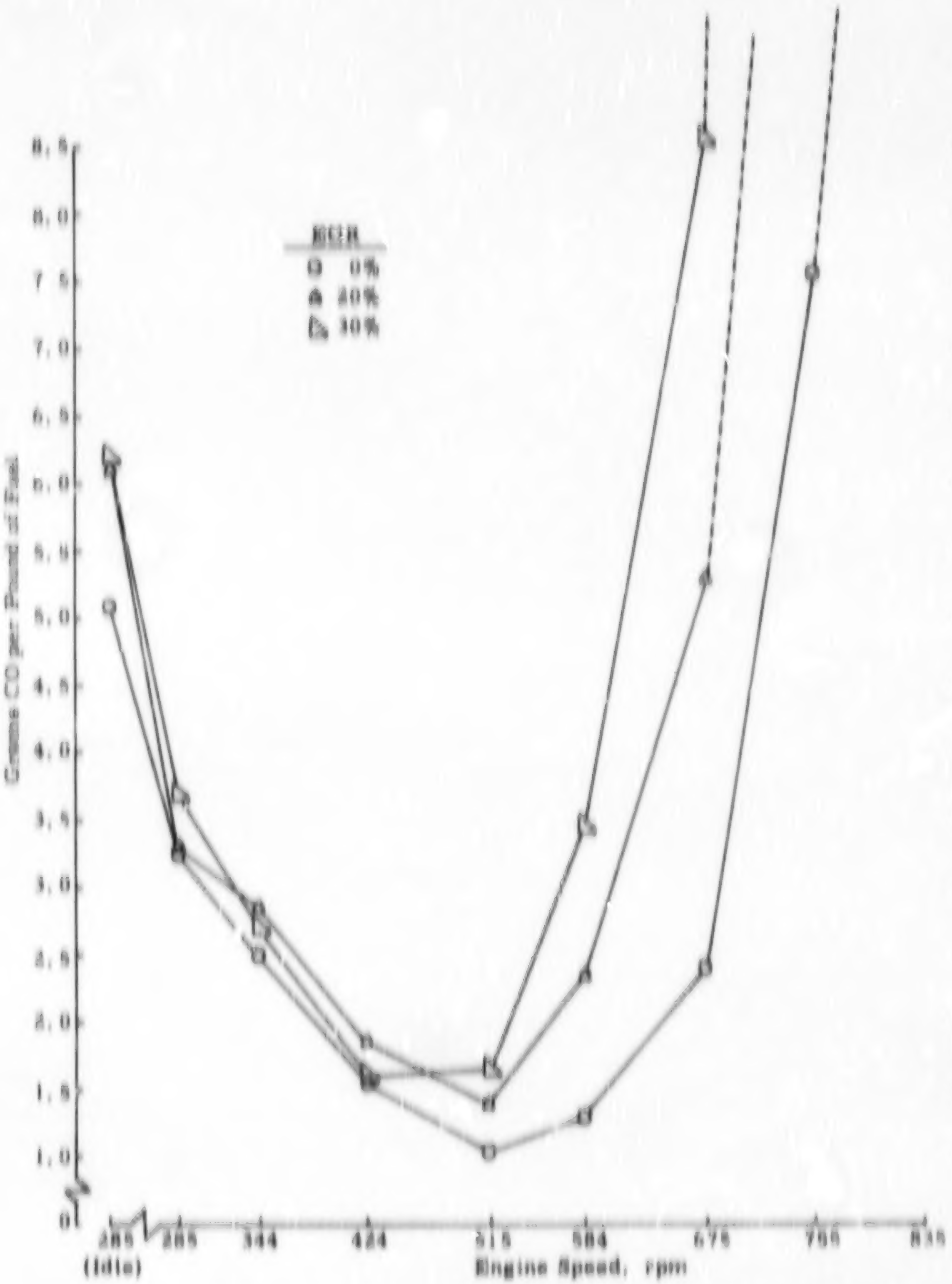

FIGURE C-71. MODAL FUEL SPECIFIC CO FOR VARIOUS RATES OF COOLED EGR--LOW-SAC INJECTORS AT STANDARD TIMING

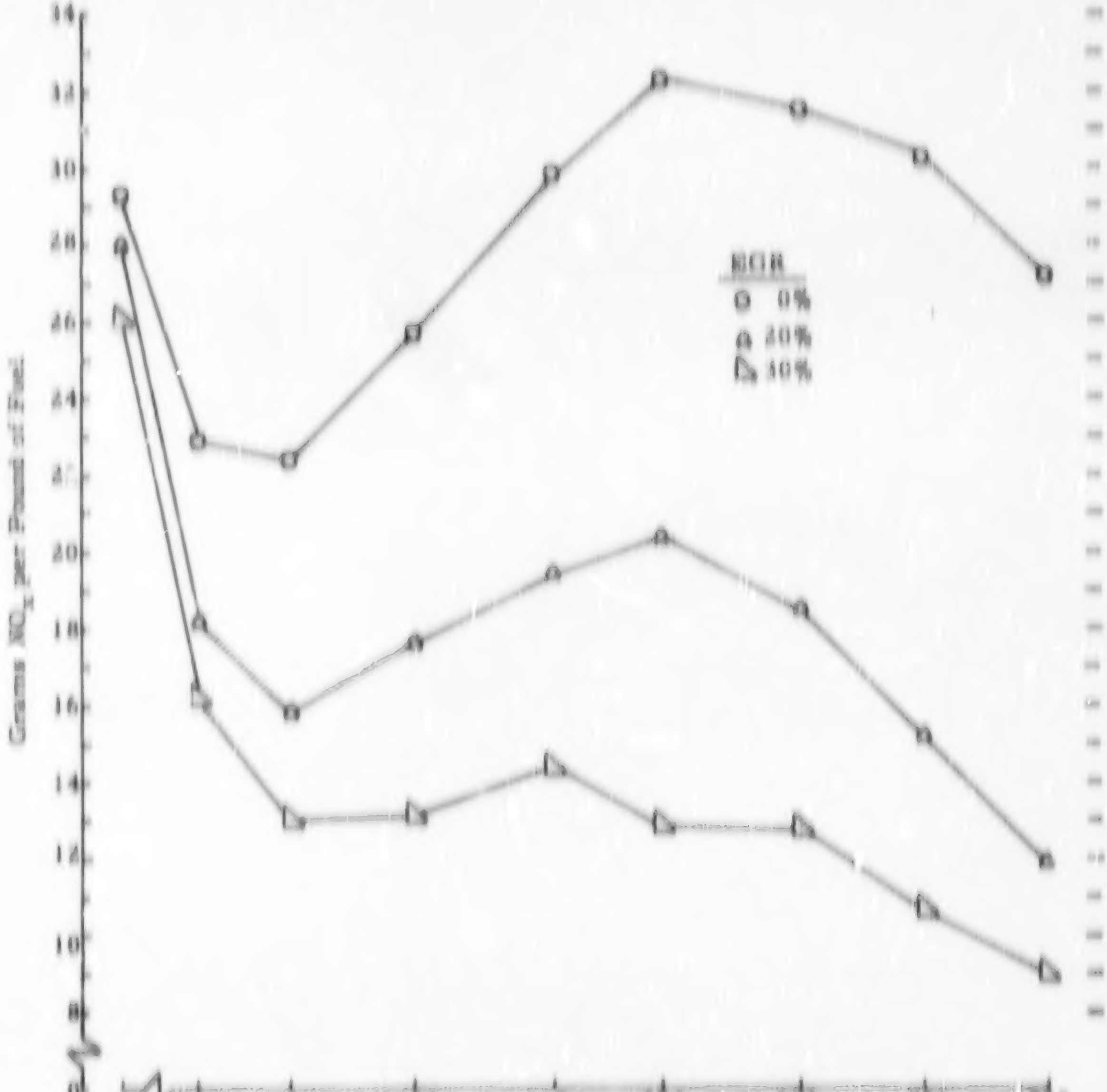

FIGURE C-72. MODAL FUEL SPECIFIC NO$_x$ FOR VARIOUS RATES OF COOLED EGR--LOW-SAC INJECTORS AT STANDARD TIMING

TABLE C-15. SUMMARY OF EMISSION CONCENTRATIONS FOR VARIOUS RATES OF HOT EGR--NEEDLE-VALVE INJECTORS AT STANDARD TIMING

Mode	Engine Speed, rpm	EGR Rates* 0%	10%	20%	30%
		HC Concentrations, ppmC			
1, 6, 11	285	142	90	94	109
2	285	158	82	84	94
3	344	139	88	92	96
4	424	154	106	112	108
5	515	176	128	135	128
7	584	184	154	157	164
8	675	232	186	200	212
9	755	272	232	240	258
10	835	288	258	265	308
		CO Concentrations, ppm			
1, 6, 11	285	59	64	63	67
2	285	66	71	71	70
3	344	77	71	62	76
4	424	63	58	61	69
5	515	58	81	80	96
7	584	82	184	252	307
8	675	252	498	778	1383
9	755	800	1246	2684	5591
10	835	1999	3723	5904	15134
		NO_x Concentrations, ppm			
1, 6, 11	285	128	134	135	133
2	285	162	212	197	205
3	344	219	259	249	262
4	424	375	420	375	385
5	515	540	520	462	433
7	584	733	677	584	492
8	675	842	737	586	420
9	755	870	759	521	311
10	835	874	703	480	226

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*Percent of air flow mass requirement per mode.

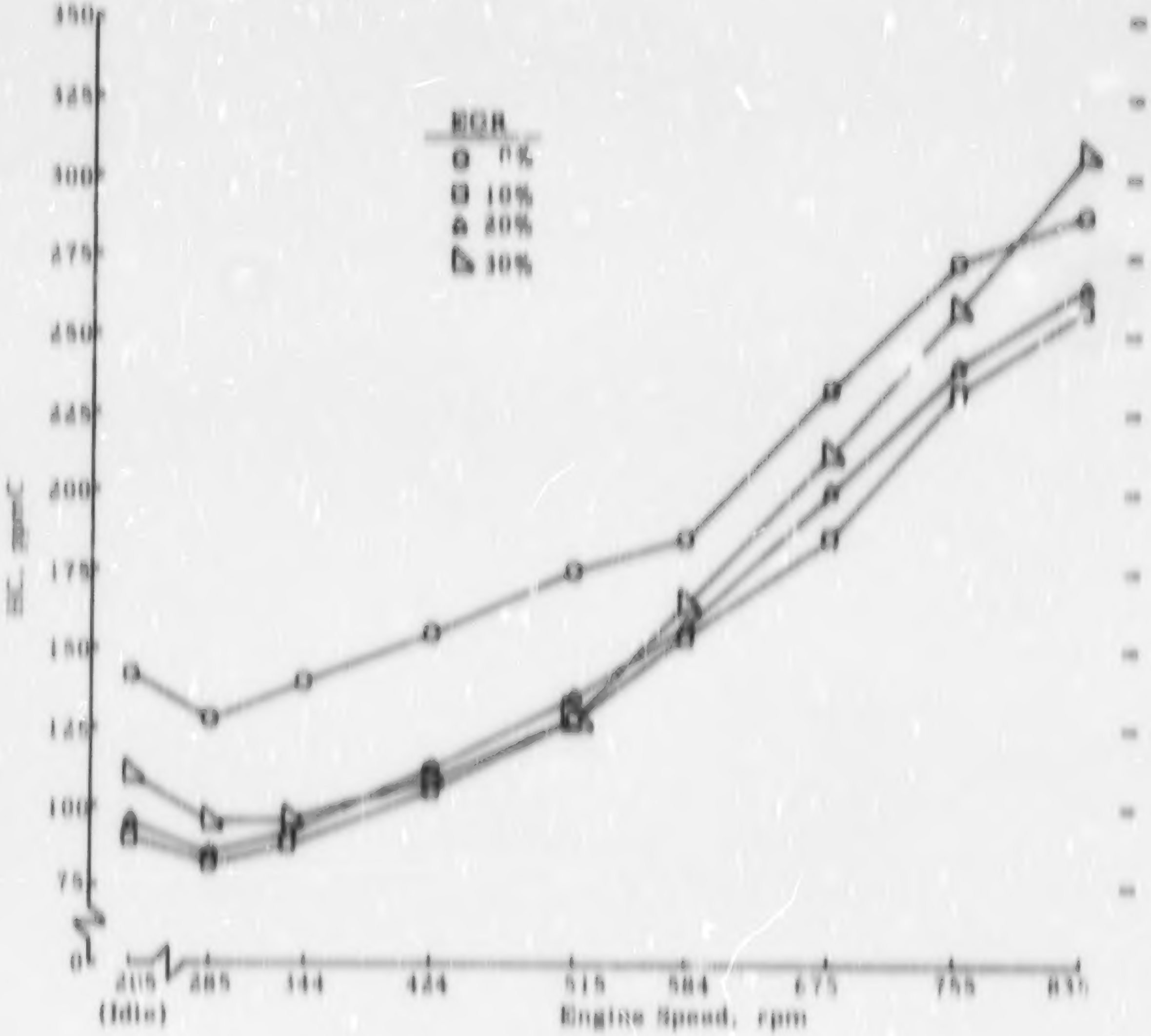

FIGURE C-73. MODAL HC CONCENTRATIONS FOR VARIOUS RATES OF HOT EGR--NEEDLE-VALVE INJECTORS AT STANDARD TIMING

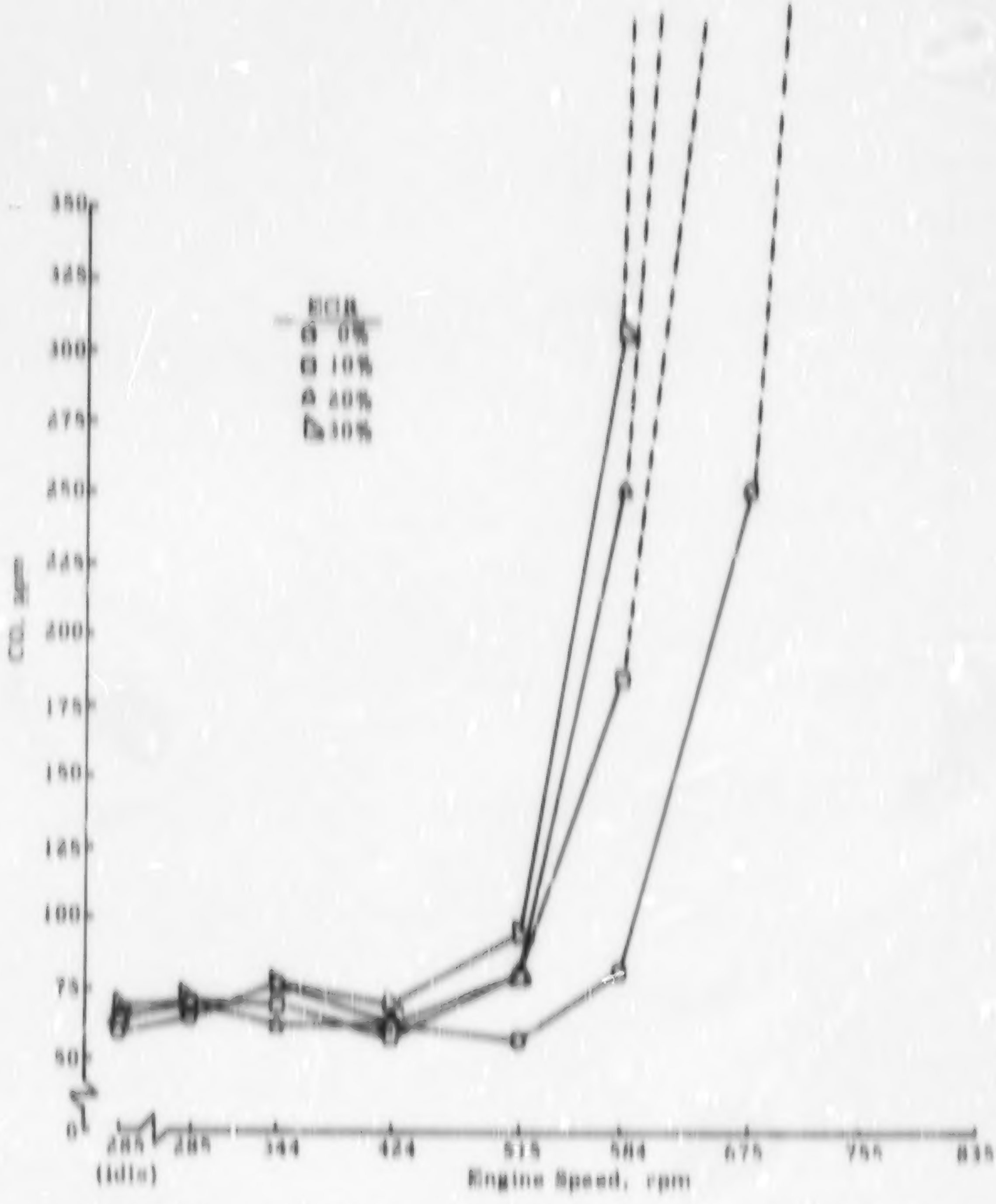

FIGURE C-74. MODAL CO CONCENTRATIONS FOR VARIOUS RATES OF HOT EGR--NEEDLE-VALVE INJECTORS AT STANDARD TIMING

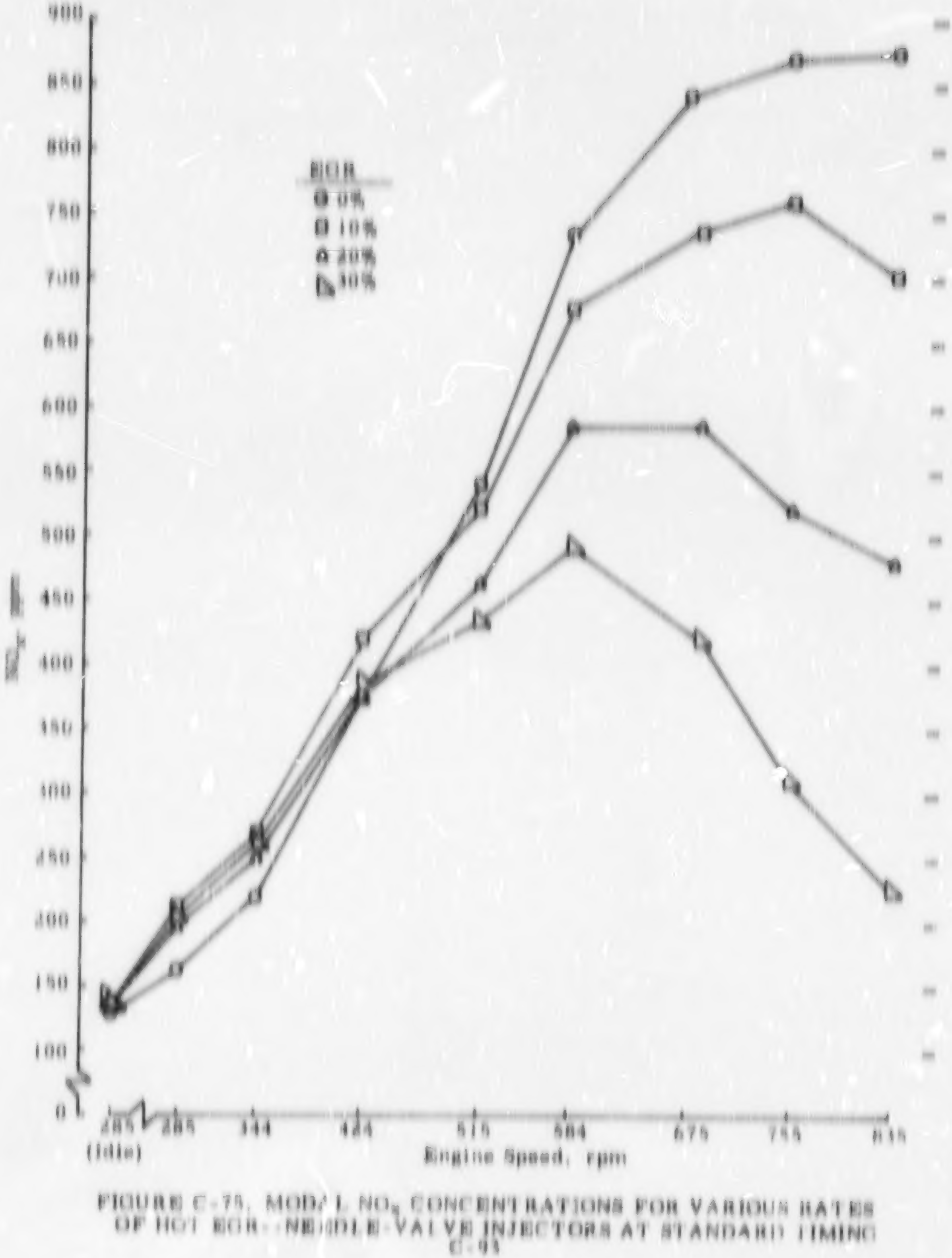

FIGURE C-75. MODAL NO_x CONCENTRATIONS FOR VARIOUS RATES OF HOT EGR--NEEDLE-VALVE INJECTORS AT STANDARD TIMING

TABLE C-16. SUMMARY OF EMISSION CONCENTRATIONS FOR VARIOUS RATES OF HOT EGR--LOW-SAC INJECTORS AT STANDARD TIMING

Mode	Engine Speed, rpm	Nominal EGR Rates* 0%	20%	30%
		HC Concentrations, ppmC		
1, 6, 11	285	68	52	71
2	285	49	53	68
3	344	61	58	73
4	424	72	63	88
5	515	81	70	95
7	584	93	78	118
8	675	125	110	165
9	755	151	165	165
10	835	181	140	182
		CO Concentrations, ppm		
1, 6, 11	285	45	86	42
2	285	63	77	47
3	344	61	82	53
4	424	54	64	52
5	515	42	69	63
7	584	65	183	280
8	675	133	630	1563
9	755	459	2674	5673
10	835	1358	6999	13743
		NO_x Concentrations, ppm		
1, 6, 11	285	158	129	157
2	285	271	202	228
3	344	343	228	250
4	424	549	392	430
5	515	750	534	553
7	584	971	726	567
8	675	1058	634	484
9	755	1121	546	348
10	835	1136	416	306

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*Percent of engine air flow mass requirement per mode.

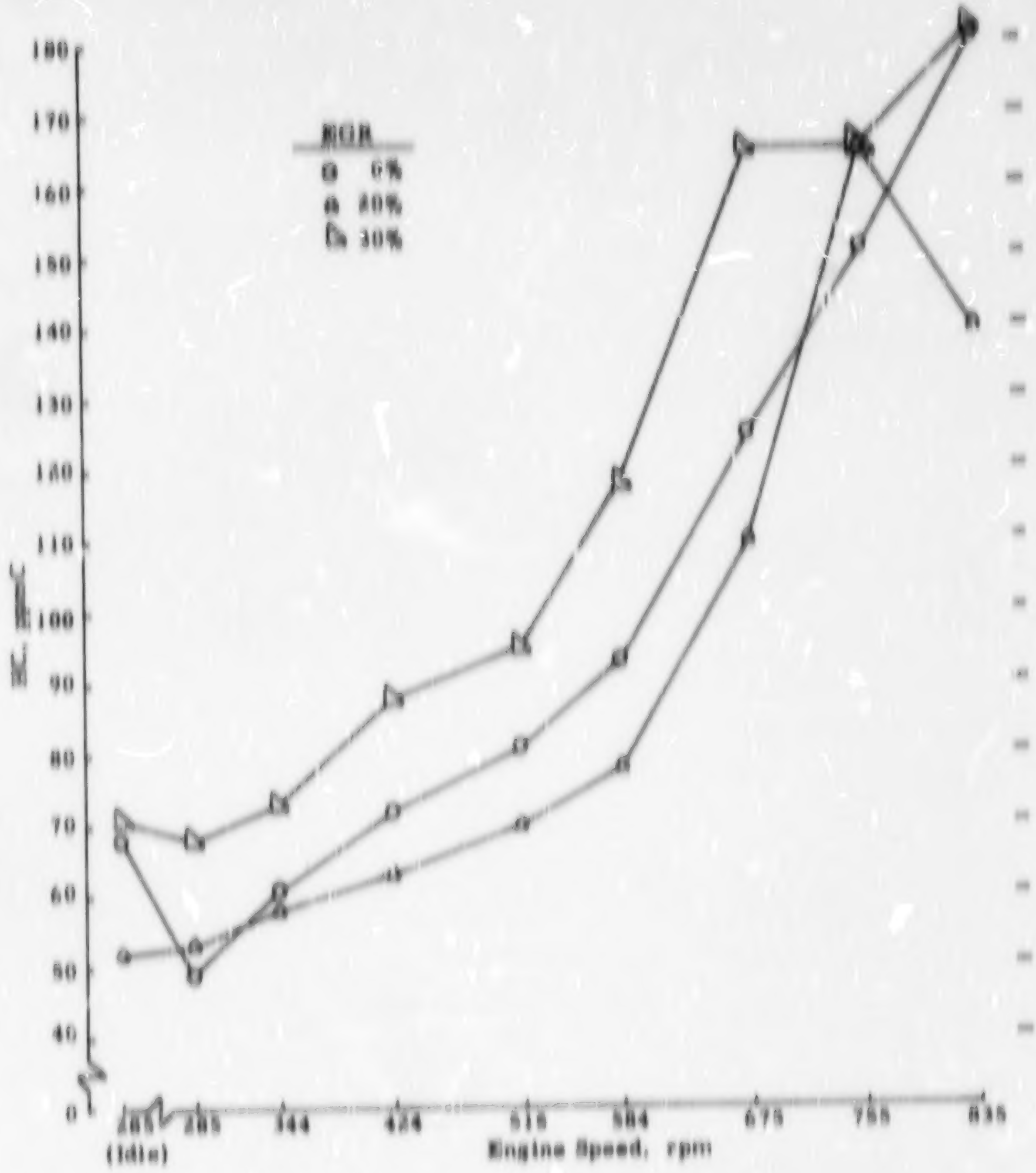

FIGURE C-76. MODAL HC CONCENTRATIONS FOR VARIOUS RATES OF HOT EGR--LOW-SAC INJECTORS AT STANDARD TIMING

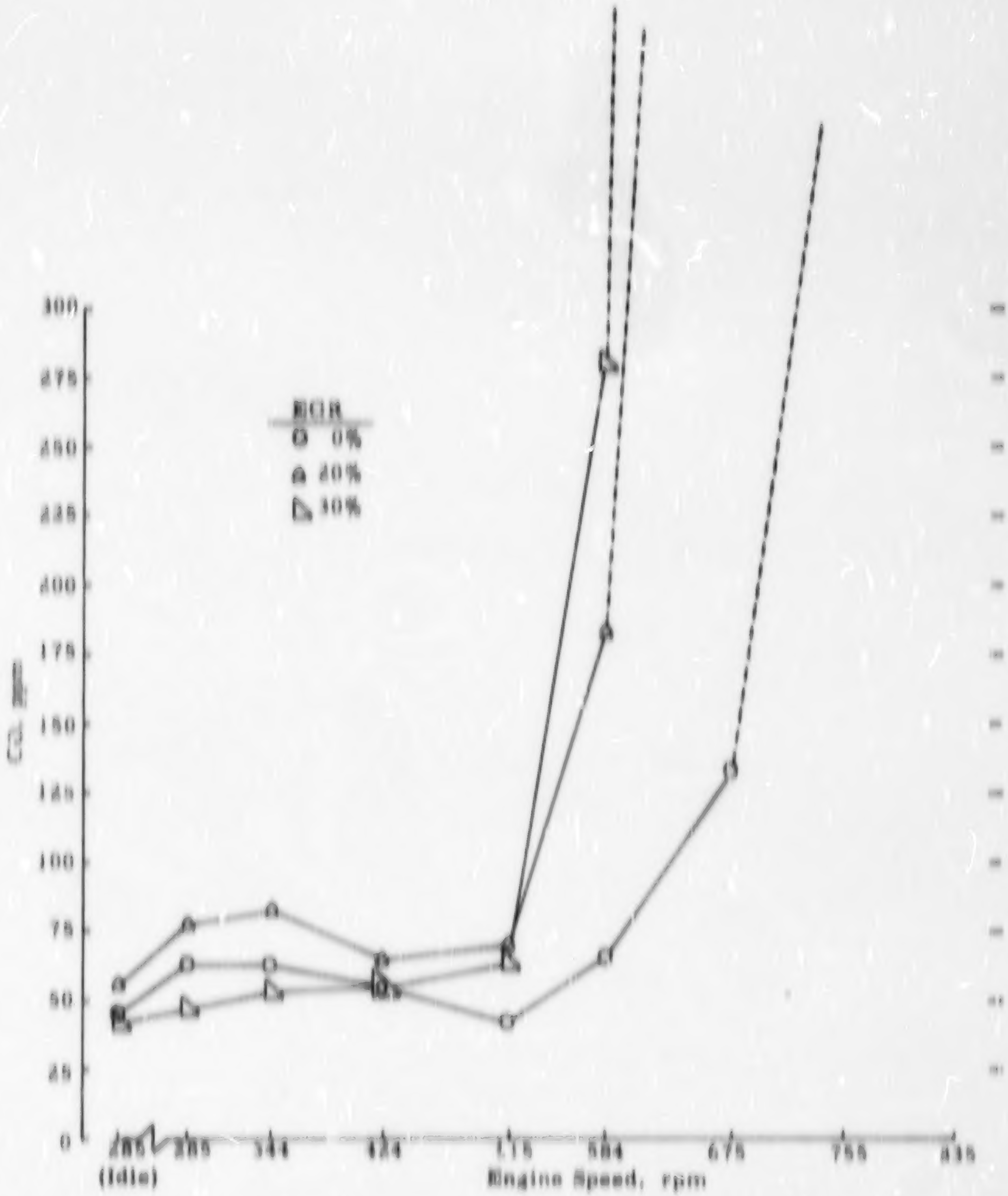

FIGURE C-77. MODAL CO CONCENTRATIONS FOR VARIOUS RATES OF HOT EGR--LOW-SAC INJECTORS AT STANDARD TIMING

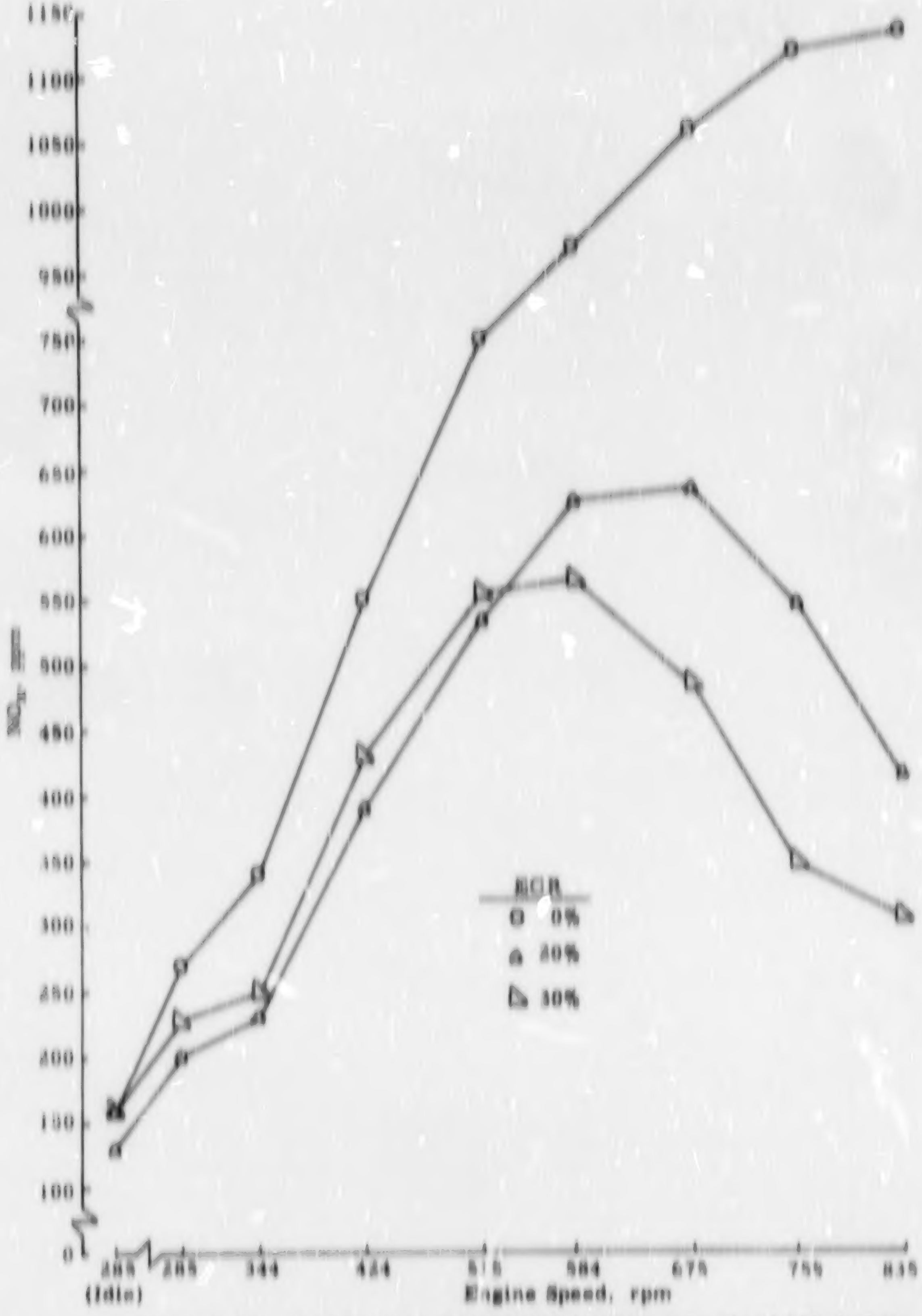

FIGURE C-78. MODAL NO$_x$ CONCENTRATIONS FOR VARIOUS RATES OF HOT EGR—LOW-SAC INJECTORS AT STANDARD TIMING

TABLE C-17. MODAL BRAKE SPECIFIC AND FUEL SPECIFIC EMISSIONS FOR NEEDLE-VALVE INJECTORS, STANDARD TIMING, AND HOT EGR

Mode	Engine Speed, rpm	Grams/Bhp-Hour HC	Grams/Bhp-Hour CO	Grams/Bhp-Hour NO_x	Grams/Pound of Fuel HC	Grams/Pound of Fuel CO	Grams/Pound of Fuel NO_x
			0% Hot EGR*				
1, 6, 11	285	-	-	-	5.60	4.60	16.52
2	285	3.51	3.70	14.53	3.54	3.65	14.61
3	344	1.80	2.06	9.22	2.68	3.05	13.79
4	424	1.06	0.85	8.47	2.07	1.68	16.54
5	515	0.94	0.61	9.41	1.96	1.28	19.69
7	584	0.81	0.70	10.17	1.71	1.53	22.27
8	675	0.89	1.92	10.52	1.94	4.20	23.00
9	755	0.93	5.46	9.75	2.03	11.89	21.28
10	835	0.92	12.70	9.12	1.92	26.55	19.06
			10% Hot EGR*				
1, 6, 11	285	-	-	-	4.76	6.62	23.13
2	285	1.16	2.00	9.87	1.94	3.33	16.44
3	344	0.84	1.35	8.40	1.58	2.50	15.75
4	424	0.62	0.68	8.07	1.32	1.44	17.15
5	515	0.62	0.77	8.14	1.34	1.68	17.80
7	584	0.61	1.44	8.76	1.38	3.24	19.70
8	675	0.67	3.56	8.65	1.48	7.92	19.26
9	755	0.73	8.00	8.00	1.64	17.96	17.96
10	835	0.78	22.20	6.88	1.60	45.79	14.20
			20% Hot EGR*				
1, 6, 11	285	-	-	-	4.37	5.80	20.35
2	285	1.07	1.78	8.17	1.79	3.00	13.73
3	344	0.81	1.10	7.19	1.49	2.00	13.21
4	424	0.57	0.62	6.10	1.19	1.30	13.05
5	515	0.59	0.70	6.59	1.29	1.53	14.52
7	584	0.57	1.81	6.91	1.27	4.06	15.48
8	675	0.64	5.00	6.19	1.41	10.95	13.54
9	755	0.70	15.71	5.01	1.48	[illegible]	10.50
10	835	0.76	33.89	4.47	1.50	66.59	8.87
			30% Hot EGR*				
1, 6, 11	285	-	-	-	4.62	5.65	18.29
2	285	0.96	1.44	6.88	1.82	2.71	12.96
3	344	0.72	1.12	6.36	1.38	2.16	12.30
4	424	0.48	0.60	5.51	1.04	1.31	12.10
5	515	0.56	0.68	5.02	1.00	1.49	11.05
7	584	0.50	1.86	4.88	1.12	4.18	10.98
8	675	0.60	7.84	3.92	1.30	16.91	8.45
9	755	0.76	32.64	2.98	1.51	65.29	5.96
10	835	0.90	75.62	2.14	1.56	132.59	3.74

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*Percent of air flow mass requirement per mode.

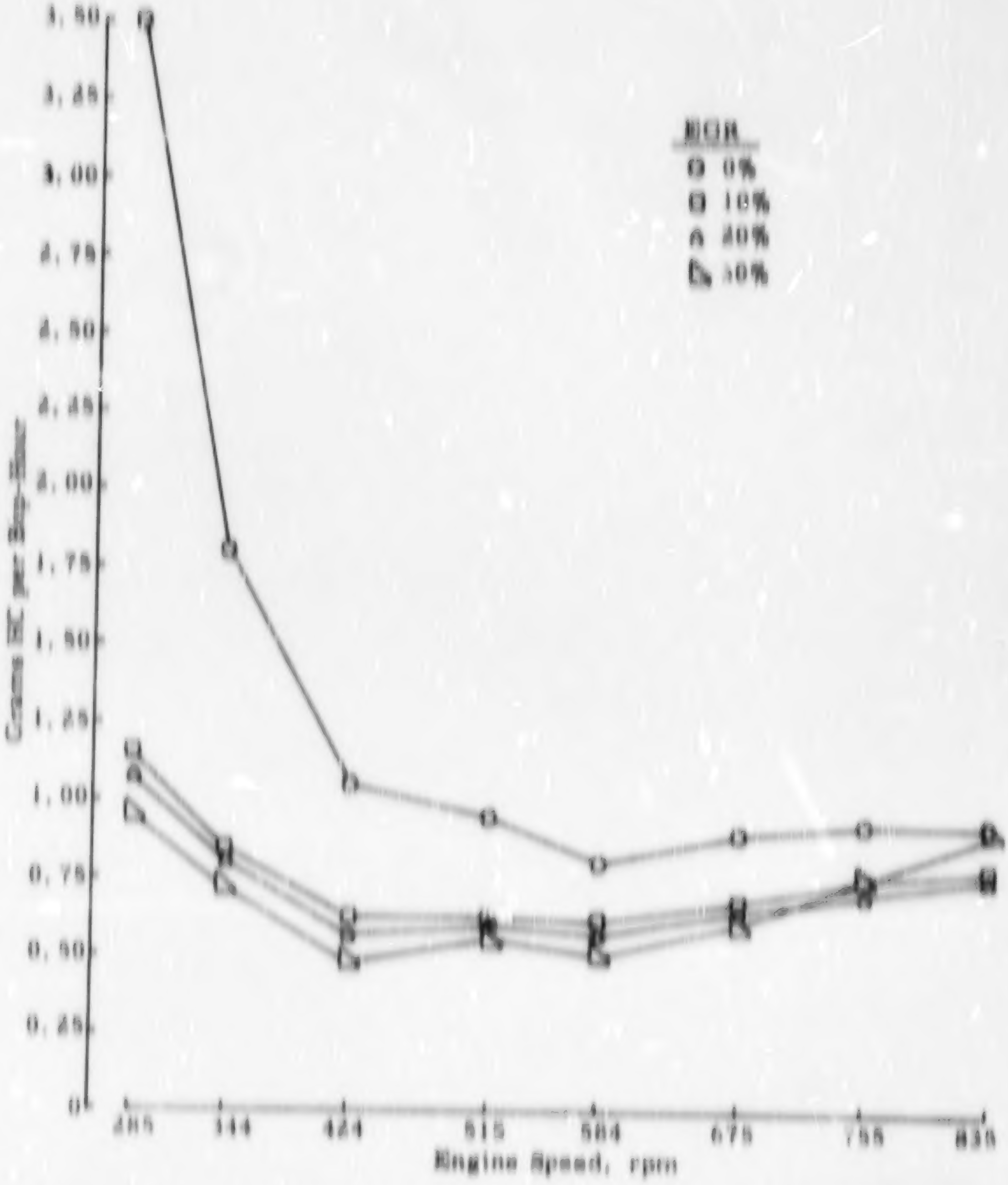

FIGURE C-79. MODAL BRAKE SPECIFIC HC FOR VARIOUS RATES OF HOT EGR--NEEDLE-VALVE INJECTORS AT STANDARD TIMING

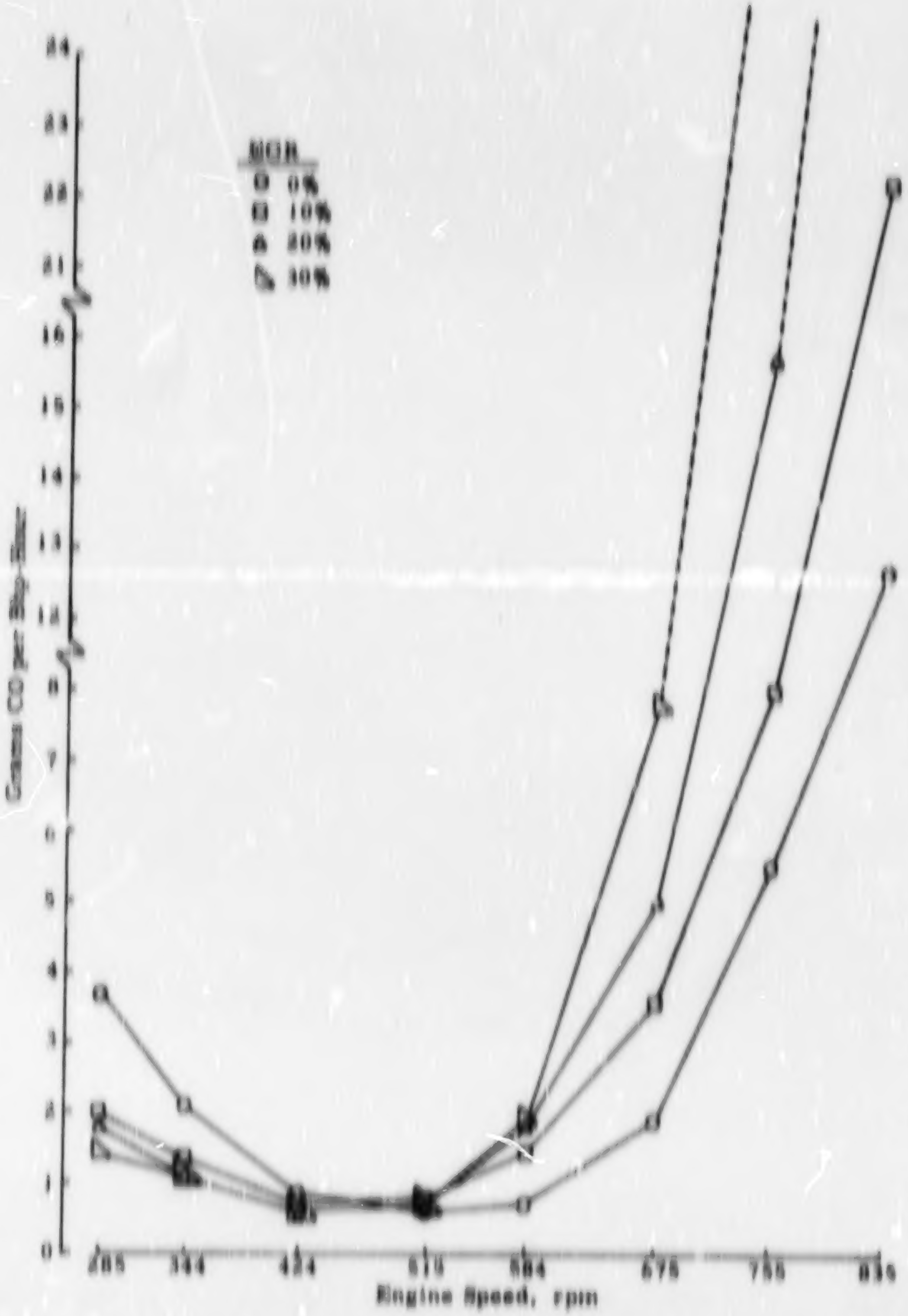

FIGURE C-80. MODAL BRAKE SPECIFIC CO FOR VARIOUS RATES OF HOT EGR--NEEDLE-VALVE INJECTORS AT STANDARD TIMING

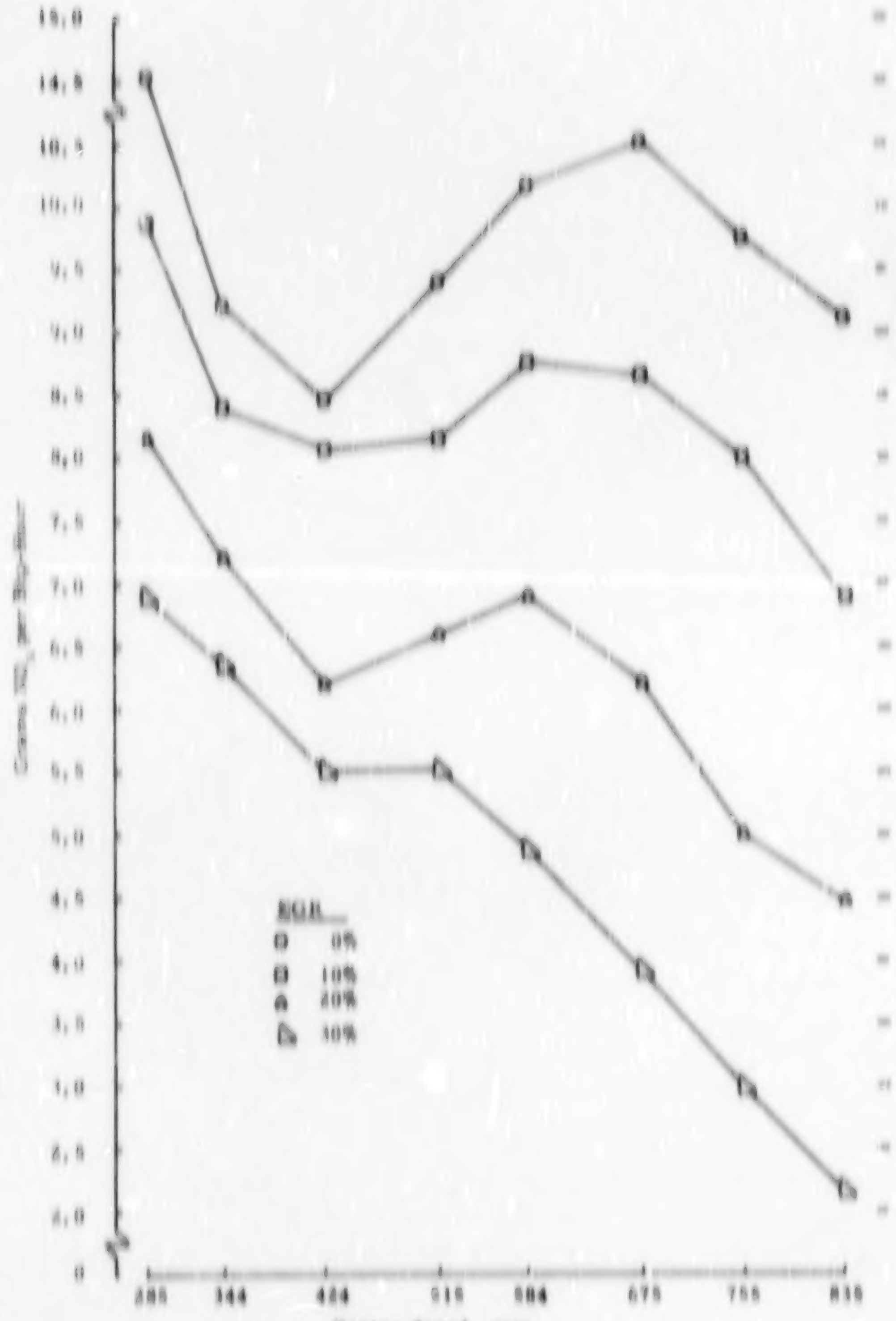

FIGURE C-81. MODAL BRAKE SPECIFIC NO$_x$ FOR VARIOUS RATES OF HOT EGR--NEEDLE-VALVE INJECTORS AT STANDARD TIMING

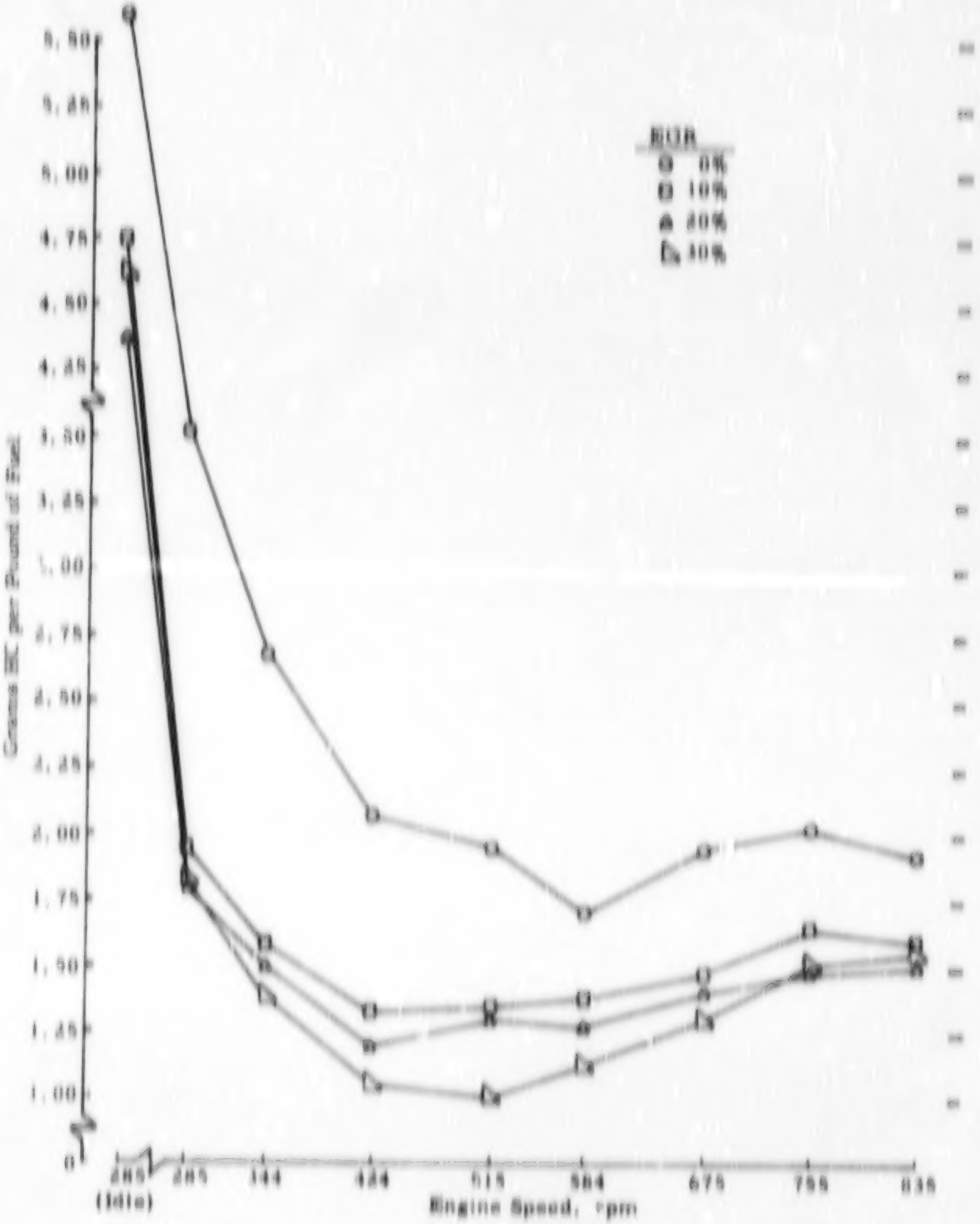

FIGURE C-82. MODAL FUEL SPECIFIC HC FOR VARIOUS RATES OF HOT EGR--NEEDLE-VALVE INJECTORS AT STANDARD TIMING

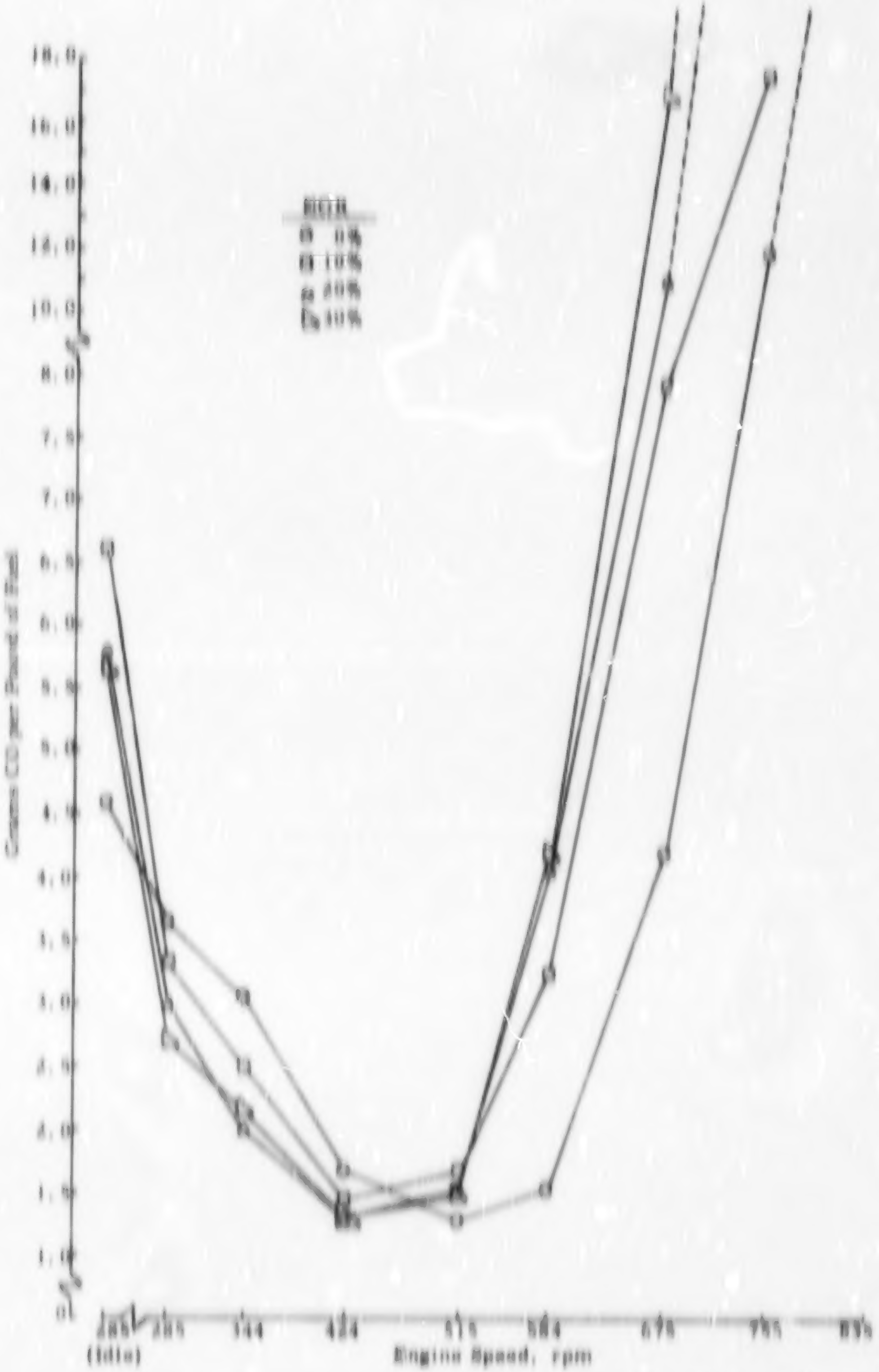

FIGURE C-81. MODAL FUEL SPECIFIC CO FOR VARIOUS RATES OF HOT EGR - NEEDLE-VALVE INJECTORS AT STANDARD TIMING

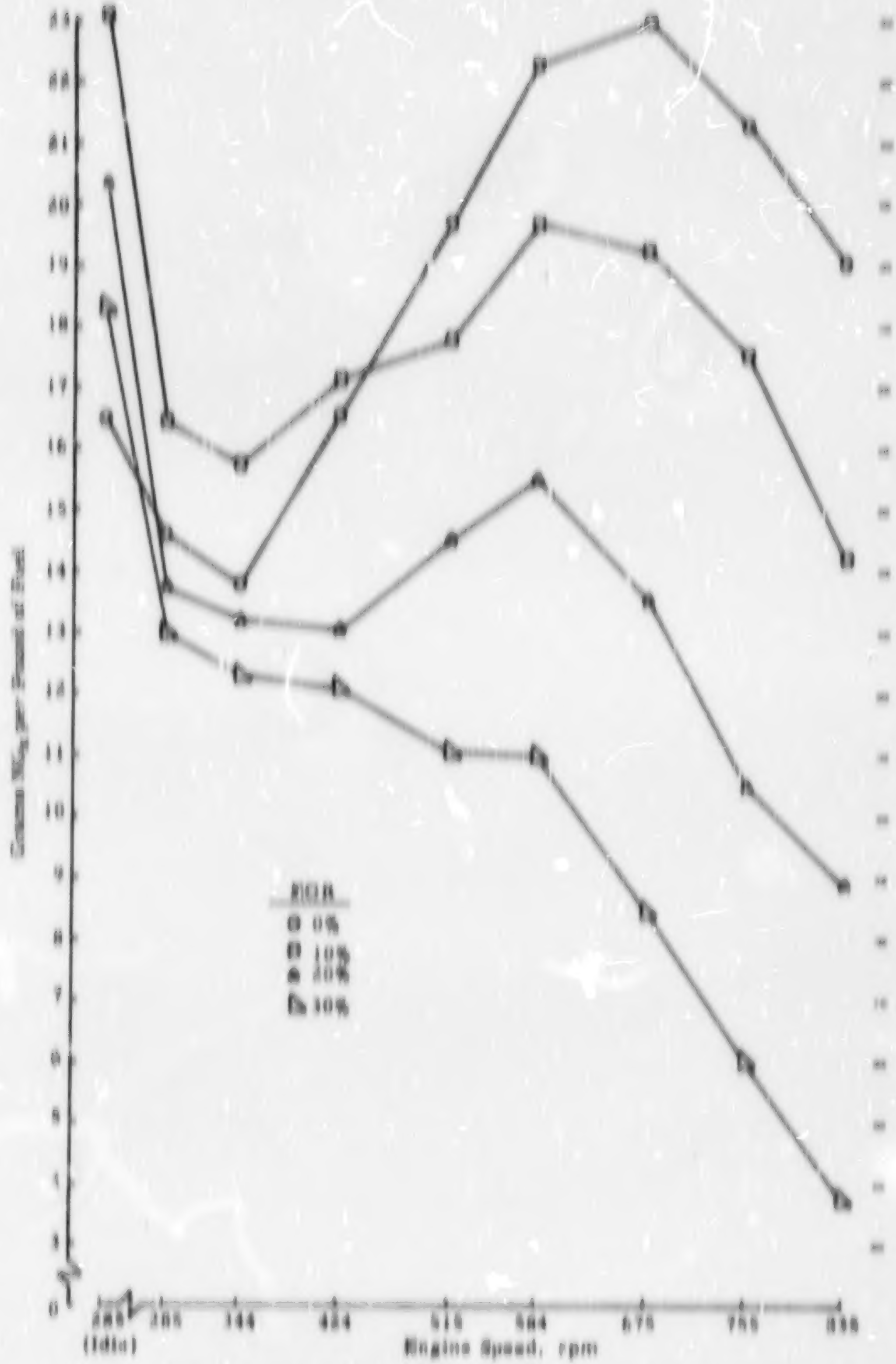

FIGURE C-84. MODAL FUEL SPECIFIC NO_x FOR VARIOUS RATES OF HOT EGR--NEEDLE-VALVE INJECTORS AT STANDARD TIMING

TABLE C-18. MODAL BRAKE SPECIFIC AND FUEL SPECIFIC EMISSIONS FOR LOW-SAC INJECTORS, STANDARD TIMING, AND HOT EGR

Mode	Engine Speed, rpm	Grams/Bhp-Hour HC	Grams/Bhp-Hour CO	Grams/Bhp-Hour NO_x	Grams/Pound of Fuel HC	Grams/Pound of Fuel CO	Grams/Pound of Fuel NO_x
			0% Hot EGR*				
1, 6, 11	285	°	°	°	3.86	5.08	49.32
2	285	0.71	1.61	12.79	1.28	3.24	32.92
3	344	0.61	1.25	11.23	1.22	2.49	28.38
4	424	0.46	0.69	11.41	1.03	1.55	25.72
5	515	0.41	0.44	12.87	0.99	1.02	29.84
7	584	0.42	0.56	13.82	0.99	1.31	32.29
8	675	0.49	1.04	13.61	1.14	2.40	31.47
9	755	0.54	3.28	13.61	1.24	7.56	30.27
10	835	0.60	8.86	12.19	1.33	19.75	27.19
			20% Hot EGR*				
1, 6, 11	285	°	°	°	2.67	5.70	21.87
2	285	0.59	1.71	7.45	1.15	3.34	14.55
3	344	0.47	1.32	6.04	0.97	2.75	12.56
4	424	0.32	0.65	6.56	0.74	1.49	15.12
5	515	0.29	0.56	7.23	0.68	1.32	16.90
7	584	0.27	1.27	7.15	0.65	3.03	17.06
8	675	0.35	4.00	6.59	0.81	9.20	15.18
9	755	0.36	16.21	5.45	1.09	35.20	11.83
10	835	0.43	42.73	4.19	0.91	80.91	7.91
			30% Hot EGR*				
1, 6, 11	285	°	°	°	3.49	4.08	24.59
2	285	0. 4	1.02	8.20	1.29	1.74	14.31
3	344	0.59	0.85	6.59	1.08	1.55	12.17
4	424	0.39	0.45	6.20	0.91	1.07	14.61
5	515	0.35	0.47	6.71	0.85	1.11	16.04
7	584	0.37	1.74	5.77	0.87	4.12	13.75
8	675	0.50	9.49	4.81	1.13	21.21	10.79
9	755	0.50	34.12	3.45	1.02	69.75	7.05
10	835	0.55	82.51	3.03	1.00	149.01	5.46

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*Percent of engine air flow mass requirement per mode.

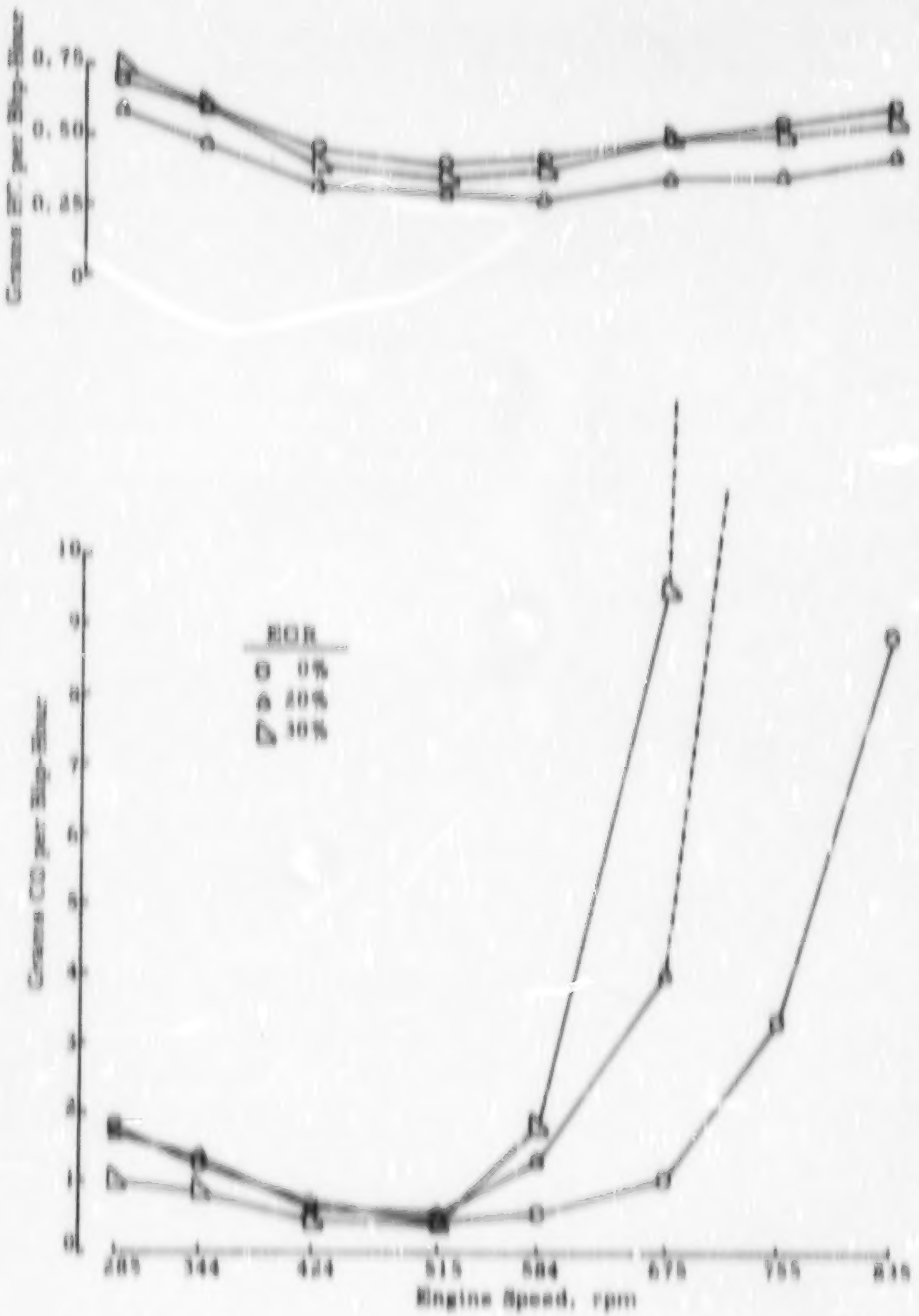

FIGURE C-55. MODAL BRAKE SPECIFIC HC AND CO FOR VARIOUS RATES OF HOT EGR--LOW-SAC INJECTORS AT STANDARD TIMING

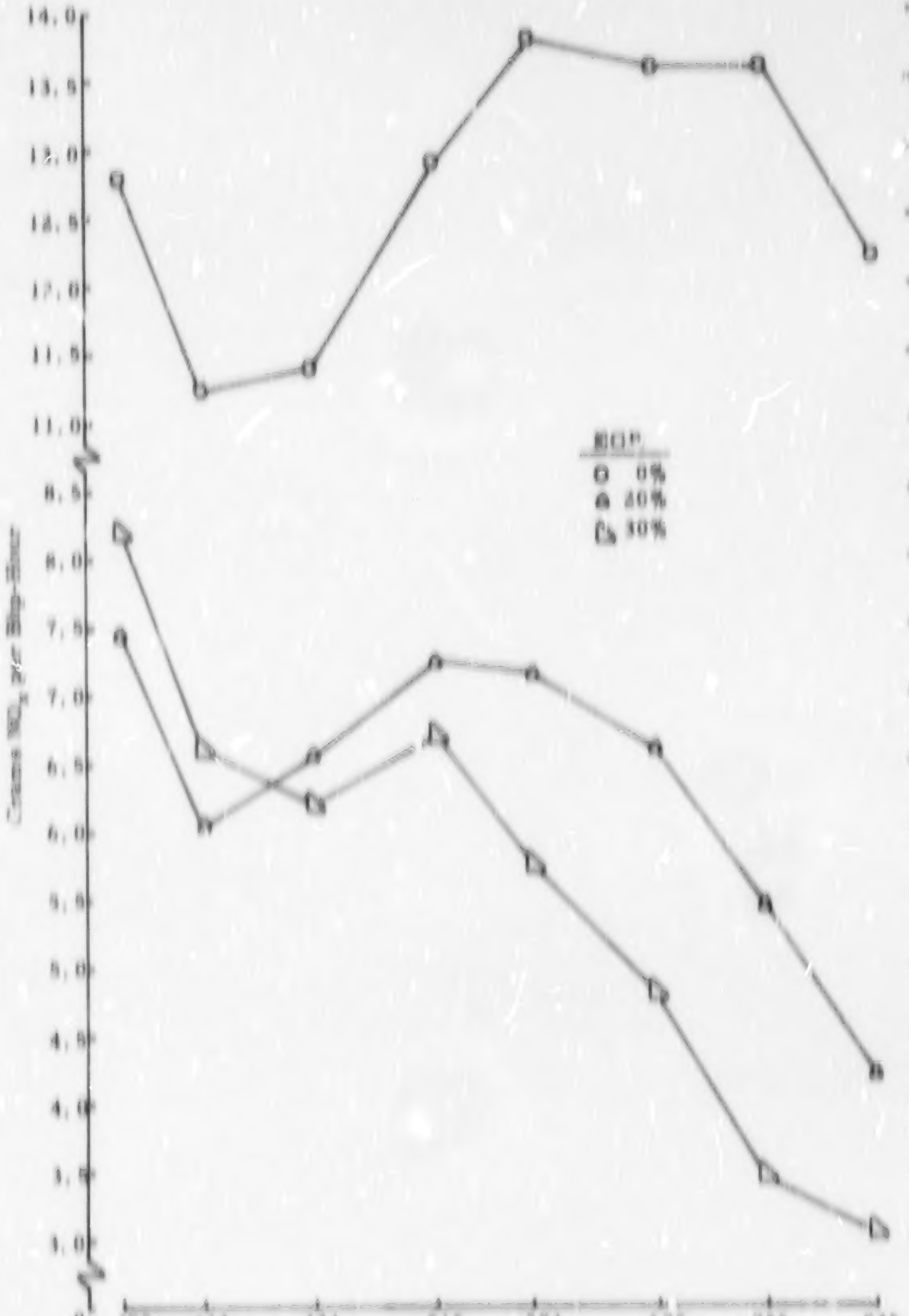

FIGURE C-86. MODAL BRAKE SPECIFIC NO_x FOR VARIOUS RATES OF HOT EGR--LOW-SAC INJECTORS AT STANDARD TIMING

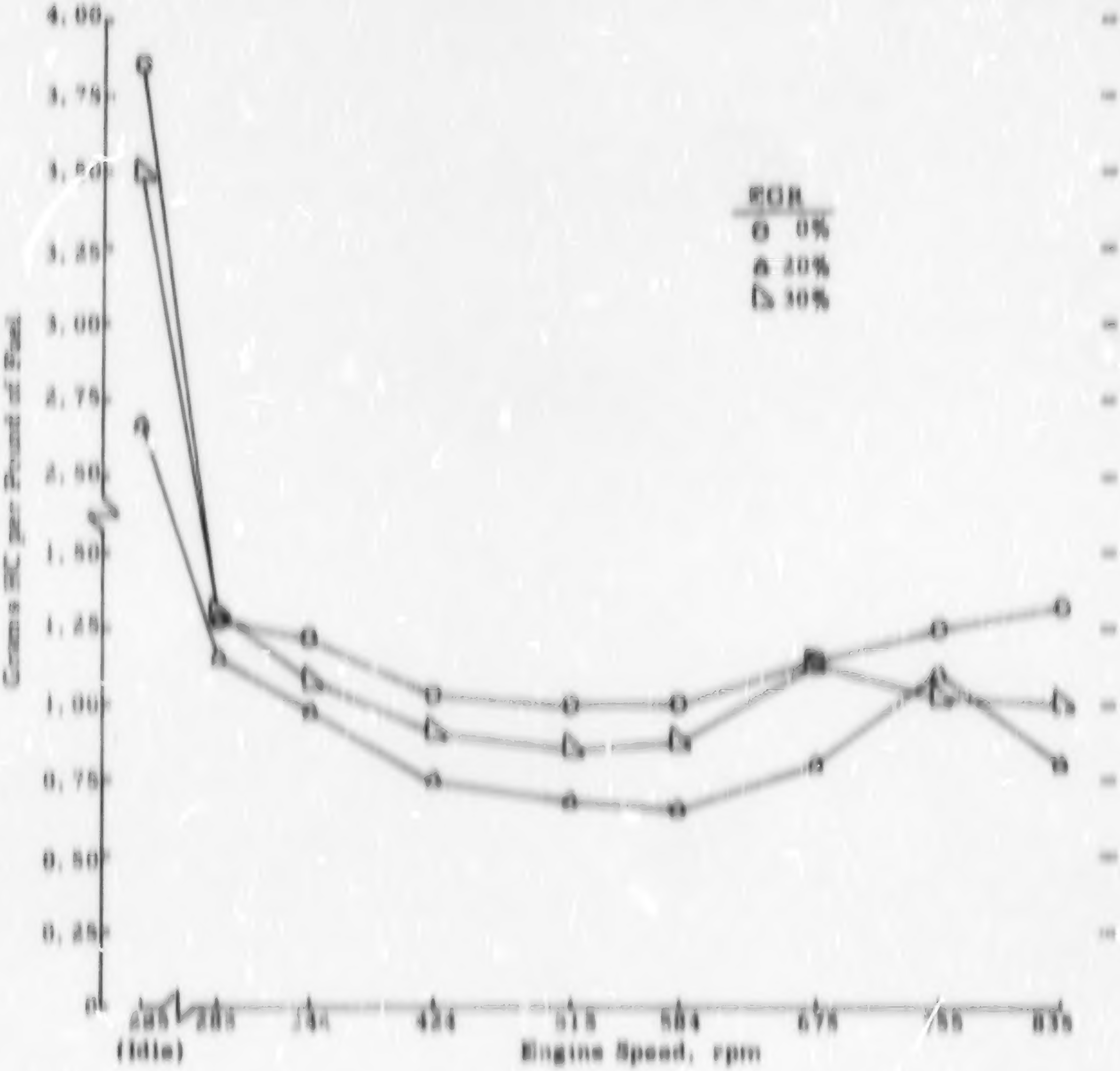

FIGURE C-87. MODAL FUEL SPECIFIC HC FOR VARIOUS RATES OF HOT EGR--LOW-SAC INJECTORS AT STANDARD TIMING

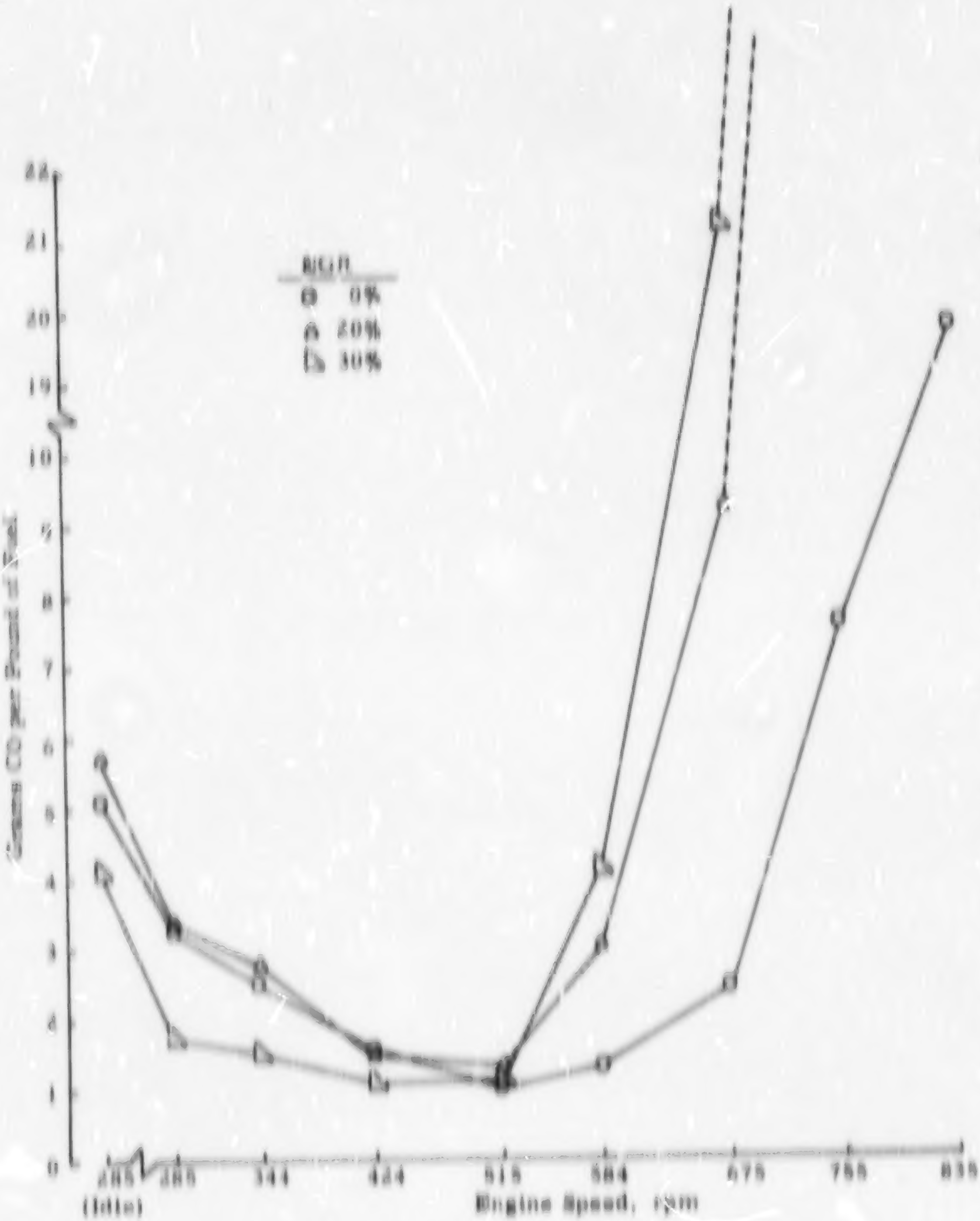

FIGURE C-88. MODAL FUEL SPECIFIC CO FOR VARIOUS RATES OF HOT EGR--LOW-SAC INJECTORS AT STANDARD TIMING

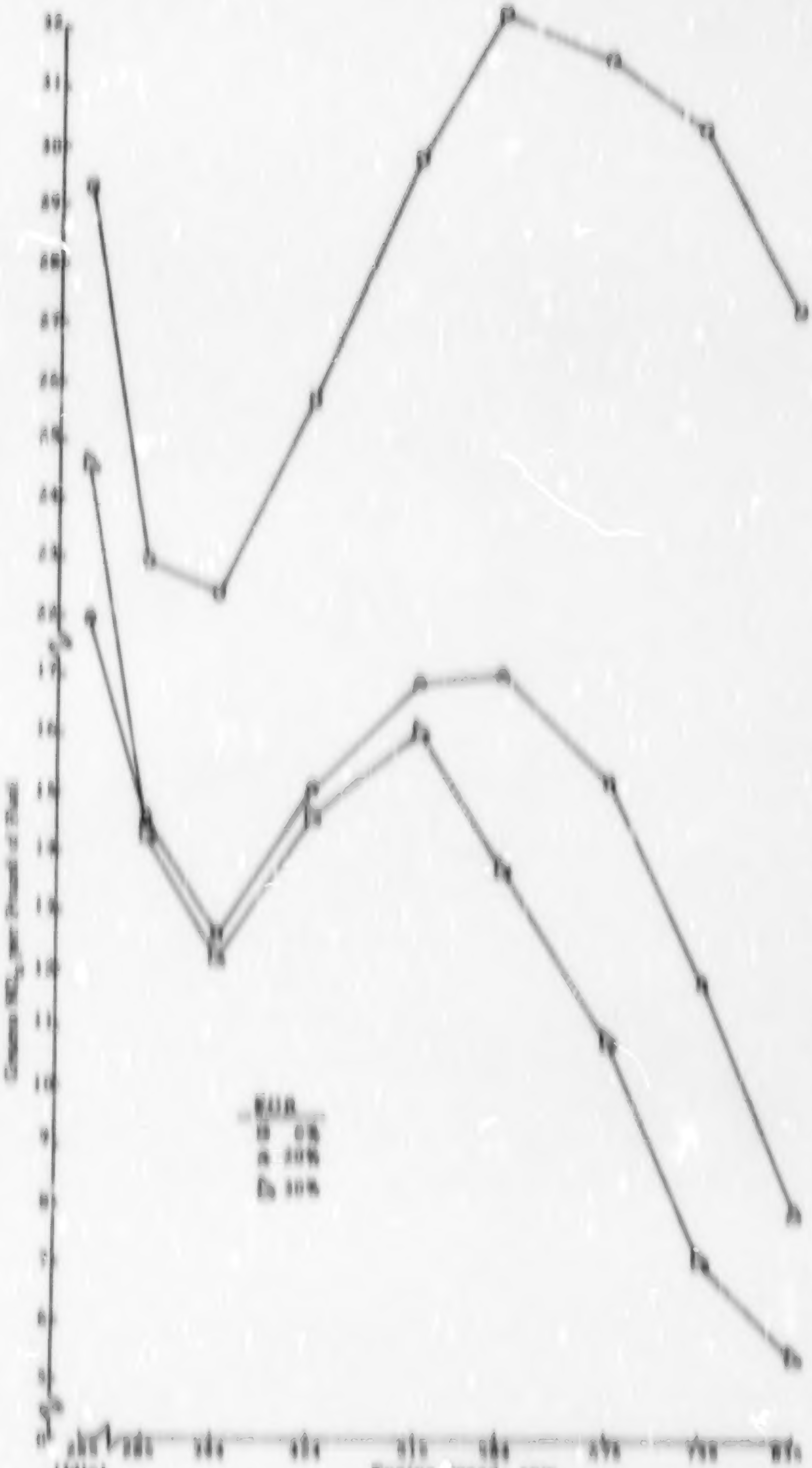

FIGURE C-97. MODAL FUEL SPECIFIC NO$_2$ FOR VARIOUS RATES OF HOT EGR—LOW-SAC INJECTORS AT STANDARD TIMING